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PHYSICS AS TECHNOSCIENCE – FROM RESEARCH LABS TO EDUCATIONAL LABS

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ABSTRACT

A central part of the enculturation of new scientists in the natural sciences takes place in poorly understood apprentice–master settings: potential expert researchers learn about success in science by doing science as members of research groups. What makes learning in such settings challenging is that a central part of the expertise they are attempting to achieve is tacit: the ideas guiding scientific knowledge-building are embodied in its practices and are nowadays rarely articulated. This interdisciplinary study develops a naturalistic view concerning scientific knowledge construction and justification and what is learned in those processes, in close co-operation with practitioners and by reflection on their actual practices. Such a viewpoint guides developing the expertise education of scientists. Another goal of the study is to encourage science education at every level to reflect as much as possible the epistemological aspects of doing science that practising scientists can also agree upon.

The theoretical part of the dissertation focuses on those features of experimentation and modelling that the viewpoints of scientific practices suggest are essential but which are not addressed in the traditional views of science studies and, as a consequence, in science education. Theoretical ideas are tested and deepened in the empirical part, which concerns nanoscience. The developed contextualized method supports scientists in reflecting on their shared research practices and articulating those reflections in the questionnaire and interview.

Contrary to traditional views, physical knowledge is understood to progress through the technoscientific design process, aiming at tightening the mutually developing conceptual and material control over the physical world. The products of the design process are both understanding about scientific phenomena and the means to study them, which means constructing and controlling a laboratory phenomenon, created in a laboratory in the same design process that produces the understanding about its functioning. These notions suggest the revision of what exactly is achieved by science and on what kind of basis, which indeed moves the epistemological views of science towards a viewpoint recognizable to its practitioners.

Nowadays, technoscientific design is increasingly embodied in simulative modelling, mediating between the experimental reality and its theoretical framework. Such modelling is neither a part or continuation of theorizing as most literature considers modelling, nor it is only a bare means to analyse experimental data, but a partly independent and flexible method of generating our understanding of the world.

Because the rapid development of modelling technology alters the evidential basis of science, a new kind of expertise is needed. The entry to the physical reality provided by generative modelling differs epistemologically and cognitively, from traditional methodological approaches. The expertise developed in such modelling provides scientists with new kinds of possibilities. For young scientists' success and scientific and technological progress, this expertise is worth understanding.

LIST OF PUBLICATIONS

This thesis is based on the following publications, which are referred to in the text by their Roman numerals:

I: Tala, S. (2009). Unified View of Science and Technology for Education: Technoscience and Technoscience Education. *Science & Education 18(3-4)*, 275-298.

II: Koponen, I. & Tala, S. (2014). Generative Modelling in Physics and in Physics Education: From Aspects of Research Practices to Suggestions for Education. In Matthews, M. (Ed.), *International Handbook of Research in History, Philosophy and Science Teaching*. Springer, 1143-1169.*

III: Tala, S. (2011). Enculturation into Technoscience: Analysis of the Views of Novices and Experts on Modelling and Learning in Nanophysics. *Science & Education 20(7-8)*, 733-760.

IV: Tala, S. (2013). Knowledge Building Expertise: Nanomodellers' Education as an Example. *Science & Education 22(6)*, 1323-1346.

* The theoretical part of the co-authored Article II (Koponen & Tala 2014), was primarily developed upon the basis of Ismo Koponen's ideas and the empirical part was primarily produced by Suvi Tala. The subsequent theoretical and empirical parts and the implications for education were developed in co-operation in such a way that the final paper provides new scientists' views on generative modelling for education.

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Helsinki, January 1st, 2015
Suvi Tala

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1. INTRODUCTION

A central part of the enculturation of new scientists in the natural sciences takes place in apprentice-master settings: potential expert researchers learn about success in science by doing science as members of research groups. What the apprentice scientists learn in such a way is worthy of considering, because it contributes to the scientific and technological progress. An important part of the expert knowledge they try to acquire is moreover tacit (for definition of 'tacit', see Collins 2010). The epistemological, methodological and sociological basis and limits of these practises are typically not made explicit in the research groups, because those questions are not so much of interest for science itself, although they can be important in education. Science and technology studies, when accompanying science education research, has a potential to improve the situation by working as a shadow discipline complementing specialist science in the production of understanding about means and methods towards progress (cf. Chang 1999; Layton 1993; Matthews 1994). In this interdisciplinary study, the basic epistemological processes of science are considered in close co-operation with practitioners and through reflection on the actual practices. The study combines both theoretical and empirical approaches in order to develop a functional view on the expertise that guides physicists' knowledge construction and justification processes. Furthermore, understanding about the basis of scientific knowledge is a natural starting point for all science education aspiring to scientifically sound content and effective learning. Science education is at the moment broadly based on the views about the products of science. When we are interested in understanding the basis, namely assumptions and methods, underlying the sciences and thus defining the possibilities and limits of science, it is essential not only to explore results, but also the processes by which scientists came to these conclusions (see Ankeny et al. 2011). On basis of the naturalistic viewpoint to science and doing science, the dissertation suggests us to revise the understanding about nature of science promoted by present science education.

This dissertation was naturally primarily motivated by an individual physics student's endeavour to understand the subject under study. At the beginning of my studies in university physics, one laboratory exercise asked me to identify particles on the basis of "their trajectories" in a cloud chamber. To be exact, the cloud chamber was broken at the time, and thus I was given a brief account of the experimental settings and a photocopy of the resulting situation. It was an easy task to perform with the given step-by-step directions, but I felt very uncomfortable with it. I did not see any connection between the lines on the photograph and the particles indicated by the established theory. At this point I recognized that the philosophical approach can support the understanding of physics. I soon anyway realized that a great amount of philosophy is useless for practising physicists, because philosophy of science has traditionally focused on scientific theories. Thus, a typical philosophical consideration of the growth of scientific knowledge concentrates on theory change (e.g., Lakatos &

Musgrave 1970; Laudan 1977; Popper 1972), but physicists certainly do not change theories as their everyday duty. In philosophy, the structures of scientific theories are seen as representing different aspects of the natural, physical world. These abstract ideas are tested by making a hypothesis on the outcomes of experiments based on lower-level theoretical knowledge, or experimental laws. The task of intervening in the world is then given to technology, which applies this scientific knowledge: the traditional views separate the fields of science and technology.

A closer look at the scientific knowledge-building practices show that the physical knowledge is not simply "discovered" from nature as obvious facts, but is rather painstakingly constructed through careful and well-planned experimentation and accompanying interpretation of the experiments. In laboratories we thus do not see scientists observing nature, neither now and nor in the earlier laboratories but actively creating, developing and running experimental settings in the production of the laboratory phenomenon under study (e.g., Hacking 1983; Kroes 2003). The relatively recent development of computers and their computational power have further increased our possibility to overcome the recent shortcomings of human beings. During the last decades, computer modelling has developed as a third methodological approach alongside experimentation and theoretical speculations. Nowadays, scientific knowledge-building often involves developing experimental processes in conjunction with a computer model that explains it. In consequence, the reality that physics opens up to us is accessed through the window of technology, which structures and configures the physical world as it is accessible to us. The connections observed between scientific knowledge-construction and the technological resources available for experimentation, instrumentation and modelling suggest revising the theory-oriented views towards scientific progress, and instead encourages the study of how scientific understanding develops from the interplay between science and technology.

At a concrete level it is unquestionable that parts of our physical world are instrumentally and technologically revealed and vice versa, technological development is frequently improved by scientific work. The great gentlemen scientists of former centuries, such as Ampere, Boyle and Cavendish, frequently improved their scientific control over the world by developing experimental skills and instruments. The interplay between the practical skills nurtured by craftsmen and scientists was evident in the development and design of telescopes, clocks and thermometers. Nowadays, "Big Science" – as, for example, high energy physics – is so closely tied to "Big Technology" that one can meaningfully speak of a single, complex phenomenon which is simultaneously science, scientific technology and technological science: technoscience. Also in nanoscience it is impossible to say where physics becomes technology.[1] Respective examples can be found in diverse areas of

1 For examples of the science of "very small", the case Andre Geim and Konstantin Novoselov´s experiments on graphene (Nobel Prize 2010), Albert Fert and Peter Grünberg's discovery of Giant Magnetoresistance (Nobel Prize 2007), or Gerd Binnig and Heinrich Rohrer's work on scanning tunnelling microscopes (Nobel Prize 1986). A good example is also the Isamu Akasaki, Hiroshi Amano and Shuji Nakamura's invention of blue LED (light-emitting diodes) awarded by Nobel Prize in Physic in 2014 for its energy-saving applications.

natural sciences, where pure science is motivated by and merged into technological research and development. Technology also becomes a mediating figure between the scientific products and the public discussion about scientific and technological research (see Postman 1985). Thus, the interplay between science and technology is evidently worth paying attention to. As a consequence, while the relationship between science and technology is studied here in the context of the practices of science, the dialogical tension between the two trajectories – that of science-driven technology and technology-driven science – is considered as a primus motor of scientific progress for much of physics, as well as a part of engineering research, but in some areas it is more visible than in others[2] (Article I). For a unified view the term technoscience has been suggested e.g., by Latour (1987). The recent views of technoscience broadly take into account the social, economic and ethical aspects[3] (see Mitcham 1994; Pinch & Bijker 1984; Postman 1985), but its epistemological and cognitive dimension needs to be extended for educational purposes.

The concept of technoscience is in this thesis developed primarily on a theoretical basis in the contexts of knowledge-building through experimentation and modelling. There special attention is paid to the new epistemological and cognitive possibilities enabled by computer modelling. Because of the lack of empirical studies on scientists' viewpoints concerning their practices, the technoscientific ideas are reconsidered and developed further from the modellers' viewpoints in the field of material physics and nanophysics.[4] Towards this end, the developed contextualized method supports scientists in reflecting on the ideas embodied in their practices and rarely – if ever – articulated in research groups. The viewpoints of the nanomodelling practitioners is worth studying more thoroughly due to the amount of research resources invested in nanoresearch. The results strongly suggest that ideas characterizing technoscience are present in the practitioners' views, which indeed provide a deeper look into the technoscientific ideas in the practices of physics, namely in the practices of modelling, also thereby extending our conceptions of modelling (Article III).

Modelling and simulations provide scientists with increasingly important sets of tools, methods and practices that complement and, in part, substitute the traditional theoretical and experimental modes of doing science. From the point of view of scientific practice, computer models and simulations are intriguing, being at the same time both highly productive and contested. A closer look at scientific knowledge construction reveals that such modelling is often neither a part nor a continuation of theorizing as most of the literature considers modelling to be (Article II); nor

2 Naturally, in physics there are also fields of research where the primary objective is in responding to the fundamental questions – and in engineering technology, there exists a variety of aims and fields which, as such, are less scientific than those mentioned here.

3 Since the social aspects of technoscience have been widely studied in the sociological literature, the views therein are already considered also in the field of education from sociological viewpoints, for example in such movements as STS (science-technology-society), STSE (science-technology-society-environment) and SSI (social scientific issues).

4 Thus, a kind of transdisciplinary approach is adopted to scrutinize the field of nanoscience and -technology, which itself is often mentioned as an example of succeed reached through interdisciplinarity (see Schummer 2004).

is modelling only a bare means to analyse experimental data. Rather, modelling constitutes, a partly independent and flexible method to generate our understanding of the world. That extends radically the limits of thought experiments, for example, which simulative modelling seems to replace in recent science (Chandrasekharan et al. 2012). For the technological base, computer modelling provides the possibility for a deeper insight into the research problems and new dimensions that cannot be reached through experimentation alone.

At the same time, the new, rapidly developing methodology transfers the expertise needed in the field. By mapping and scrutinizing the expertise (Article IV), which young scientists are achieving through working, we can support the poorly understand process, in which novices are enculturated as researchers in the field. Thus achieved, this contextualized understanding about science and doing science can be used in developing science education also at the lower levels. Another goal of the recent study is to encourage science education to reflect as much as possible on the epistemological aspects of doing science as well as the aspects that practising scientists can also agree on: this goal can be referred to as providing an "authentic picture of science" and as commenting on the discussion about (the) "nature of science" for science education (Articles I & II; Tala 2013b; Tala & Vesterinen 2015).

2. ANALYSING SCIENTIFIC KNOWLEDGE AND ITS CONSTRUCTION

Many historical scientists provided insightful analyses of the grounds and limits of their field in those same treatises that we would now identify as the 'contents' of science. For a rather uncommon example of such a physicist, Pierre Duhem (1914) presented insightful views on the essential role of instruments and apparatuses in the experimental processes of physics, while the contemporary philosophy of science concentrated on theory. Nowadays, when the fields of research are increasingly specialized, such analysis is rarely presented in the scientific discussion. However, a scientist's success is still based on an understanding of the methodological, epistemological and social rules underlying the research of the field and the scientists' ability to deal with those tacit, developing ideas. The basis of the scientific practices is studied in the HPST (History, Philosophy and Sociology of science and science Teaching) tradition, by means of historical, philosophical and sociological analysis accompanied by psychological and educational viewpoints. During the last couple of decades, HPST viewpoints have served numerous educational reforms and curricula-planning worldwide (Adúriz-Bravo & Izquierdo-Aymerich 2005; Matthews 1994; Schulz 2009). Such an approach is here suggested as being fruitful also at the highest levels of education, in the education of new scientists. The thesis focuses on the philosophical ideas about science nurtured and learned in the practices of research groups, paying attention to those epistemological ideas which the practitioners themselves consider to be most important. Figure 1 presents the theoretical basis of the thesis, which is discussed in this section.

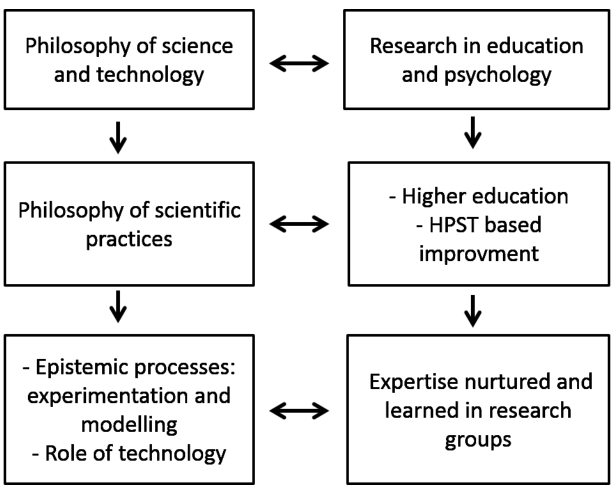

Figure 1: The background of the research in hand.

At the moment, the central philosophical question of how science succeeds in achieving reality has been answered in education on the basis of several different philosophical views. A favoured view within science education has been scientific realism in its different forms, the central idea of which is that the scientific theories aim at truth and sometimes get close to it (realism of theories). Thus the entities, states and processes described by correct theories are assumed to really exist (realism of entities). Contrary to this realist stance, constructivism has been promoted instead. This view emphasizes knowledge as being relative and thus also emphasizes the role of experience in judging the viability of knowledge (Glaserfield 1987; Quale 2008). At its core, the constructivist stance includes a subjectivist, empiricist, and personalist understanding of human knowledge, including scientific knowledge. Indeed, the later emphasis considering the role of experimentation in the scientific knowledge-building process has been noted in the educational discussion. It has given birth to a view called new empiricism (Cartwright 1983, 1999a; Koponen 2007; Sensevy et al. 2008; van Fraassen 1980), where at the core of physics is the process in which theoretical predictions are seen to connect with experimental data (e.g., Koponen & Mäntylä 2006). Modelling and simulations have been widely and for a long time used in building up the complex but intimate relation between theory and experimentation (e.g., Galison 1997; Keller 2003; Winsberg 2010). As stated above, this dissertation work suggests an approach called technoscience, which is developed with the aim of improving the picture of science stated by previous views. In paying attention to the intertwined relation between experimentation and theory, it shares much with the new empiricism. Moreover, the viewpoint of technoscience pays special attention to the underestimated role of technology – understood in its entirety from instruments and machines to technological knowledge and practices – in scientific knowledge construction through experimentation and modelling. It differs in many respects from existing established views, but by the same token it also borrows from and synthesises many existing ideas and notions. Therefore, a resume of the recent epistemological background finding its way in this discussion is presented in section 2.1.

The technoscientific view was primarily developed on a theoretical basis, as informed by the practices of science; the view was then tested and deepened in co-operation with the practitioners themselves.[5] By concentrating on the practices and the ideas that guide them, a functional and at the same time a kind of minimal view on scientific knowledge-building was reached. Scientific knowledge-building involves not only individual minds, but also essentially involves the collective. In the process of accepting knowledge (and methods), the Kuhnian idea seems to hold; there is

5 The practise-oriented approach to science and knowledge became prominent within social studies of science in the 1980s (Latour 1987; Pickering 1992) and later gained a stronger hold of the philosophy of science (Chang 1999; Giere 1999), and then linked up also with the contemporary research in a variety of fields (Schatzki et al. 2001). The plainly philosophical roots of such an approach can be found in naturalists', pragmatists', operationalists' and late-Wittgensteinians' attempts to ground truth and meaning of ideas in practises. Recently, a growing number of philosophers and historians have noticed the importance of understanding scientific knowledge construction practises.

no standard higher than the assent of the relevant community (Kuhn 1962).[6] The decisions of relevant communities are not necessarily correct; nevertheless, that is the court which judges whether the research questions and methodology are relevant or not (2.1.4). In their education towards expertise, young scientists learn to produce scientific knowledge in line with the shared scientific understanding, including both the recent state of conceptual understanding and the available and allowable means on which it is developed. Experts, who have more social power in terms of defining the rules of the scientific game, also excel by developing their cognitive abilities. As a result, an expert has meaningful and well-connected knowledge and skills that can be applied to new tasks in the field in question. The previous studies on expertise have largely concentrated on the social and psychological aspects introduced in section 2.2 together with pointing out the type of expertise mapped in this study.

2.1 BACKGROUND IN THE PHILOSOPHY OF SCIENTIFIC PRACTICES

In science text-books, physics is introduced in conceptual form, which emphasizes the structure of knowledge as hierarchically organized concepts, laws and theories. As a heritage of a theory-oriented tradition, this structure of scientific knowledge is well articulated by philosophers. From the epistemological viewpoint, science is anyway defined by the methodological practices where knowledge is produced. This thesis focuses on the experimentation and modelling together with the technology employed and developed in them. On the one hand, experimentation is epistemologically vital: it is the basis for justification in physics. On the other hand, experimentation without connection to theory is meaningless. Nowadays, computer modelling often takes a central role in building up those connections. The section that follows introduces how the structure and nature of scientific knowledge and experimentation and modelling, as a means to produce that knowledge, are understood in this thesis.

2.1.1 Engineering Scientific Knowledge

Current science education largely seeks a philosophical basis for understanding scientific theory, from the Semantic View of Theories (SVT) that originates from the work of Suppes (1962), Suppe (1977), van Fraassen's (1980) constructive empiricism and Giere's (1988) constructive realism, where knowledge is mainly understood to be expressible by way of words, symbols or as conceptual abstractions. In the SVT, the task of theory is to present a description of phenomena within its 'intended scope' so that one can answer questions about the phenomena and their underlying

6 Many Kuhnian and post-Kuhnian philosophers refer to 'the scientific community' as a group of equal experts who somehow reach consensus and who take part in defining the truth within that community (see Kuhn 1962; Latour 1987). Many others who study the practices of science (e.g., van Fraassen 1980; Nickles 1989; Hacking 1983; Harré 2003) see "the scientific community" as a heterogeneous group of practitioners, who may have different views, but have a shared objective. In each case, the practitioners share the process of acceptance, the rules of which are considered in this study.

mechanisms (Suppe 1977). The phenomena are addressed in terms of models, and these hierarchically organized conceptual models constitutes scientific knowledge (see Giere 1988). At the top of the hierarchy are models of theory guiding the construction of the models at the next lower level (level of general laws) and these models guide construction of the models at the next lower level etc.. Knowledge, in turn, becomes developed in mutual interaction between models at different levels. In these interactive developing processes, knowledge of the different levels are brought in line with our cognitive structures and shared scientific understanding of the success of current scientific theories in explaining the materialization of experimentation. The best-known position of SVT made by Ronald Giere (1988, 1999), suggests the lowest level of the system of models to be constituted by visual models, such as free body diagrams and other charts and graphs. By testing the theoretical models on the lowest levels, knowledge attains an "empirical adequacy" (van Fraassen) or "similarity" (Giere). The semantic view does not provide an answer as to how the models at the lower levels are fitted with experimentation, namely how the "empirical adequacy" (van Fraassen) or "similarity" (Giere) between the models of the lower levels and their empirical testing is reached. The notion that the abstract, conceptual models cannot be directly compared with the "nature" these abstract ideas describe, motivated this dissertation study to focus on the practices in which those connections are built.

Because the final justification of scientific knowledge requires engineering of the laboratory phenomena (Article I) and even virtual phenomena (Article III), the technological knowledge employed and developed in building those connections to the experimental world are worthy of consideration when discussing scientific knowledge (Tala 2013b). Design is the central mission of engineering (Mitcham 1994; Vincenti 1990). In addition to producing material and non-material artefacts, the engineering process aims at a special engineering knowledge guiding the design processes, for example. In this way, design constitutes the cognitive bridge that crosses a spectrum from abstract, idealized conceptions to concrete, highly complex products of technology existing in the real world. Moreover, design does not (necessarily) require hands-on efforts. Rather, it is seen as the evolution of the ability to build a functional piece of technology, which can be tested and judged in a symbolic world to certain extent (see Rothbart 2007), through different kinds of thought experiments. Both functional and descriptive knowledge is produced in such a design process. As far as the conceptual form is considered, engineering knowledge shares the same general form with scientific theories – it is hierarchical in nature – and uses concepts similar to those used in science (for examples, see Vincenti 1990). The following stages of engineering knowledge have been recognized: (1) technical know-how including sensorimotor skills or technemes, (2) functional rules or "rules of thumb" and structural rules, (3) technological laws and (4) technological theories (see Mitcham 1994; Vincenti 1990), in addition to which is required at least a degree of socio-technological understanding. For the hierarchical nature and the unity of the material world that engineering knowledge describes, the levels 2-4 can also be seen to be constituted as a structure of models developing in mutual interaction similar to the way scientific knowledge is perceived.

As a consequence, when discussing technological knowledge and thinking it is apparent that knowledge is not only conceptual, but can also be technical or a processural ability and embodied in material artefacts and techniques (cf. Baird 2004; Rothbart 2007). This understanding is in this study applied to the design of experimental systems and instruments. In order to be answered in the physical world, the theoretical "why" and "what" questions are in science translated into a series of "how" questions. Then both functional and descriptive technological knowledge develops also in the scientific experimentation and modelling (Tala 2013b). Because means of "intervention" in the material world constitute the basis of science (Hacking 1983), by designing them one can said to be designing scientific understanding as well (as studied closer in the result sections 4 and 5). Finally, scientific and technological knowing become developed in mutual interaction with experimental control over the physical phenomena under study.

2.1.2 Experimentation as the Epistemological Core of Technoscience

According to views held for most 20th-century philosophy, experiments are for testing the scientific theories, namely the predictive consequences of theories, are tested without concern as to how the theories are obtained. In this case, the experiments are used in the role of what can be called the consequential justification of knowledge (for a detailed discussion, see Nickles 1989). In fact most of 20th-century philosophy has been dominated by such a distinction between the logic of justification and discovery, which in philosophy was formalised by Reichenbach (1938). However, discovery and knowledge generation was seen as a major and integral motive behind experimentation in many 19th-century philosophies, such as Whewell's (1840) philosophy of science as well as Pierre Duhem's (1914) views on science. Then the more recent philosophy of science has rediscovered the role of experiments in generating knowledge and thus brought this process under closer scrutiny. This has led to the generative view (see Nickles 1989), which transports both experimental and theoretical results into knowledge construction and justification process.

Examining the practices of working scientists provides evidence that both the consequential and generative schemes are true. Whichever approach is used depends on the phase or stage of the work in progress (for examples, see Chang 2004; Hacking 1983): sometimes the experimental work is generated entirely by theory and some experimental work does not have any theoretical explanation. Some theories spring from pre-theoretical experiments and some still wait for experimental connections, and, indeed, in many cases the practice ends up configuring a mesh puzzle of these different possibilities (for examples, Franklin 1986; Hacking 1983). Of importance here is that, in both views, consequential and generative, the relationship between the scientific experiments and the conceptual understanding is the focus. These relations are constructed through technological action and in technological mediums. Experimentation is then used by a scientist as a means to actively intervene in the material world, in order to acquire answers to the detailed how questions, which is then used to support the more hypothetical generalizations. If these generalizations can be used as a basis for successful predictions, through consequential justification, the circle is closed and new knowledge is acquired. Some recent authors have also restored the balance dominated previously by theory, in favour of experiment in the spirit of Hacking's theses: "experimentation has a life of its own" (1983, p. 150). It is this above described type of generative conception of experimentation which lies at the core of the technoscientific view. Focusing on the central role played by instrumentation in such an experimental process (and its development) supports understanding about how development of experimentation is intertwined with the development of theory at different levels.

Technology is needed to reach the cognitive goals of physics: on the one hand, the capacities of technological capability lead to the productive capacities of experimental science, and, on the other hand, capacities are revealed by technological instruments. From the typical methodological point of view, technology is employed, for example, in order to overcome imperfections and limitations in human perception by providing measurement equipment, to standardize the modes of sensation in collecting data and to process that data. For physicists scientific technology counts as more important; knowledge, techniques and material instrumentation (Mitcham 1994) constitute a bi-directional medium through which they draw their concepts of physical "reality" (e.g., Ihde 1979). These notations call for re-considering what exactly is produced in the scientific process and what the nature of such production is (section 4 and Article I). The question is even more complex in research areas where experimentation is extremely limited and where computer modelling thus plays a central role. Computer simulations are often referred to as virtual experimentation. The name is misleading in many senses, because recent modelling is epistemologically and ontologically different and partly independent from other methodological approaches.[7]

2.1.3 Scientific Knowledge Construction through Modelling

The rapid development of the role of models and modelling in science is inherently bound to the development of modelling technology and, as a consequence, computational methods. The onset of computational methods in science took place in the 1950s when researchers began to use new creative simulation methods in such diverse fields as nuclear physics, climate research, operation research and game theory. This development is continuing at an increasing pace with new areas of research and application and also potential disciplines emerging, which often carry the prefix "computational" in their names. This refers to the method in which the computer software is able to quickly calculate the simulated situations on the basis of the algorithms embodied in it. The rapidly developing roles of models and modelling have generated extensive discussion in science studies and, as a

7 To be exact, the reaction to the progress of computer modelling has been at least twofold: In conservative views, computer simulations are thought not to add any new epistemological or ontological dimensions to the classical bi-polar spectrum between rationalism and empiricism. Thus, such simulations are seen as mathematical though experimental or as a technical means. A second reaction is that such modelling is being identified as a genuinely new, third method of doing science between though experiments and material experiments.

consequence, the model-based view (MBV) in science education as well (see Article II; Gobert & Buckley 2000). Much of the inspiration for the model-based view derives from the notion that models are central knowledge structures in science (e.g. SVT) and vehicles for developing, representing and communicating ideas, but the presented views do not yet encompass the variety of roles which models play in recent scientific practices. The views to modelling prompted in science education together with their philosophical underpinnings in the recent science studies need attention and re-consideration in order to define the essential epistemic aspects of models and modelling in scientific knowledge-building practices.

The literature on modelling mostly considers it as deduction from theory in order to analyse particular unknown situations, and therefore sees it as a part, or direct continuation, of theorizing. Even in the cases where models are not directly derived from theory, theory is nevertheless thought to guide model development (e.g., Winsberg 2003, 2006). Consequently such modelling is thoroughly discussed where well-established theory already exists, such as hydrodynamics or continuum mechanics, which allows the derivation of a set of dynamical equations, the solution of which requires further modelling (see Winsberg 2003, 2006). At least when considering the cases where neither an established theory nor well-known targets exist or where experimentation is extremely limited by technological ability, the conception of models has to be extended. The role of realistic describing and predicting is not enough when describing the usage of models in studying complex system behaviour, or even in the more traditional field of nanosystems (considered in the empirical part of this thesis), for example.

The viewpoints of practising scientists' concerning models and modelling often seems to be flexible and dynamic, allowing the employment and development of different kinds of models in the different states of knowledge-building practices. The recent theoretical perspectives that take into account the concrete practices of science seem to provide a wider viewpoint regarding models and modelling, which indeed highlight the role of technology in modelling activities better than previous studies (Article II and section 4.2). This thesis also suggests that considering how engineers use models may support understanding of the role of models in science: engineering scientists build various kinds of models, ranging from mathematical models and simulations[8] to synthetic models and theoretical engineering models, which allow reasoning of artificial objects and instrumentally reliable interventions in the world. From the viewpoint of understanding modelling practices it is interesting that, in their modelling, the engineering scientists study phenomena in much the same fashion as natural scientists actually do (cf. Boon & Knuuttila 2011; Knuuttila & Loettgers 2013, 2014; Nersessian & Patton 2009).

The philosophically central question of how the relations between reality, modelling and the other methods employed are constructed is important also for modelling

8 By simulations is here referred to running a model on a computer in order to study its dynamics, which is more than a visualization or demonstration of the already known. In science education employed ready-made applets for demonstrating theory (which are often called simulations) are not simulations in this sense.

experts. The science studies have defined the relations between models and reality in different ways giving them a variety of roles (Bailer-Jones 1999; Koponen 2007). In spite of having a different perspective on models, philosophers analysing science and its models have generally agreed that models are representations[9]: we gain knowledge from them because they represent target objects in the world in some relevant respects which, on the other hand, is seen as the most essential epistemological dimension of the use of models and modelling.[10] Such modelling includes denotation (connecting the model to the phenomenon modelled), demonstration (running the model) and interpretation of the results (Hughes 1997) or parallel steps (cf. Crawford & Cullin 2004; Halloun 2007). The typical view launched by the philosophers of science is to consider models as *realistic* representations of the world[11], the task of modellers being to develop the models in order to sharpen this representational relation. The view of models as realistic bridges to reality provides a robust background in using models and modelling for the purposes of science education in the context of predicting and in explaining. For such purposes it is sufficient. Nevertheless, this viewpoint is not broad enough to explain scientific knowledge-building. For example, in science education the influential (and above introduced) views of Giere (1988, 1999) and Bas van Fraassen (1980) on modelling, say little about the methodological aspects of producing a relationship between models and the world, as one accesses it through experiments and the accompanying computer modelling. Because this question is of central importance in both building scientific models and using them in scientific knowledge construction, it is an essential question (at least) in higher education, where new scientists are educated.

The view which seems to be familiar also to practitioners of science comes close to constructive empiricism (cf. Nersessian 1995), where models are seen as empirically adequate structures, making it possible to represent and produce empirically reliable knowledge effectively. In the constructive account, theories are instrumentally valued: they can be true, but they do not need to be true in order to be usable and beneficial. Nersessian (1995, 2008), for example, who sees models as means (and tools) to represent ideas as well as reality, emphasises the cognitive aspects of using models without overarching emphasis on philosophical realism and thus provides a flexible viewpoint to SVT: seeing SVT as a developing structure (or network) of models related to each other in different ways, leaves adequate space for empiricism,

9 For example, Bailer-Jones (2003), Hughes (1997), Suárez (1999), Giere (2004), see also Hestenes (1992, 2010).

10 For example, in logical empiricism a quite direct one-to-one relation between the abstract models and reality is seen. Later, in semantic views (Giere 1988, 1999; van Fraassen 1980) the 'similarity between certain features of a conceptual model and certain observable features of a laboratory phenomenon respectively, are discussed. The model presumably represents, in some way, the behaviour and/or structure of a real system; the structural and process aspects of the model are similar to what it models (Giere 1988, 1999). 'Representation' is a broad concept (see Hughes 1997). Indeed, the practitioners' viewpoints often seem to be quite flexible, in any case (Article III).

11 The realistic position seems to be favoured also in the field of science education (Adúriz-Bravo & Izquierdo-Aymerich 2005). See, in the educational literature referred Giere (1988, 1999), also Black (1962) and Hesse (1963).

realism and pragmatism. Such a usage of models extends the image of modelling as an independent method. This idea is further developed in the result sections 4 and 5 and in Articles II, which by being grounded in theoretical and empirical analysis, provides a new view of knowledge construction through experimentation and modelling for science education.

There remains the question, however, when we are *satisfied* that agreement between a virtual or theoretical model and a laboratory phenomenon (whatever it is) is achieved. In many cases just this problem lies at the core of scientific disputes and controversies. The problem seems to be that there is no objective, sociologically neutral or unambiguous method to settle this question (see e.g., Nola 1999). Rather, any methodology which manages to demonstrate material success could become accepted. In understanding the rules of this process, social aspects cannot be simply bypassed – epistemology becomes intertwined with sociology. Although this dissertation study focuses on the epistemological side, it has to be first explained how the consequences of the social constructivistic nature of science is acknowledged.

2.1.4 Social Aspects Undermining Scientific Knowledge Construction

Constructivism states that we do not have any direct access to the external, objective physical reality which natural sciences is assumed to be explaining. Instead, the theories are seen as socially justified cognitive constructs, developed in the interplay with the material world. The different interpretations of constructivism vary broadly in regard to the consequences.

The classic views of, for example, Collins (1985) and Latour (1987) present social factors of knowledge creation as undermining rather than supporting the justification process. According to these views experimental accounts are believed and become authoritative through social institutional power. In this case, the technical knowledge and standards on which the experiments rest are seen as the pure functions of the social power of the group performing them. In such a view, laboratory apparatus and instrumental techniques are seen as rhetorical devices rather than a means to study the actual states and events of the physical world. For example, for Latour (1987), the idea of nature is invoked by the winner of the controversies, and the winner imposes the rules of future research of “the phenomena”. In this extreme, where the defence has no other basis than social and cultural negotiation, ‘external physical reality’ plays no role in the process of knowledge-building. A radical constructivist, Ernst von Glasersfeld, for example, ended up with similar consequences, when considering the situation from the psychological viewpoint of an individual (Glasersfeld 1987). Although scientists do not share this outlook in its radical form (see Newton 1998), at least not as their motivational working view (Fine 1986), this extreme view nevertheless seems to have something to say about the ways in which scientific truths become established and winners of the truth are awarded (see Friedman 2001). The more moderate views see the bearing of the social dimension on epistemology as being more positive, as supporting the processes of science.[12] They acknowledge the rather indisputable fact that scientific inquiry is a social process and that reasoned judgment is itself socially defined. Therefore, it is natural and necessary that the logic of science has a certain social background.

Furthermore, it has to be acknowledged that a strict separation between "non-epistemic" (social, personal and professional interests) and "epistemic" (cognitive) factors in the scientific process would be unrealistic (e.g., Kitcher 1990; Machamer & Osbeck 2004). As well, the inner (scientists) and outer (the public audience, companies, governments, organizations of different kinds) circles cannot be strictly separate when analysing science. In the analysis of technology, it may be more natural and it has been widely noted how the social, political and psychological factors motivate and guide the research and developmental processes (e.g., Bijker 1995; Mitcham 1994). Those factors are generally considered extrinsic to the scientific process itself (cf. Kitcher 1990, 2011; in science education, e.g. Sandoval 2005), but for practising scientists it is natural that they have a large-scale impact on knowledge-building. It is evident that the dependence of huge technological resources and thereby the interest of big financiers, for example, influence the research from its objectives to methods employed and even the results reached, to the extent that this dependence can shape the objectivity (of which climate research is an apparent example).[13] Recognizing that science is done not by logical subjects working in isolation, but by people with a variety of personal and social interests, who co-operate and compete with one another, we can finally improve both our vision of nature and our ways of learning more about nature (see Kitcher 2001).

In sum, on the one hand, science is here not seen as the monologue of a unanimous community; on the other hand, in the light of scientific and technological progress, reducing science to sociology would be an absurd exaggeration. This kind of moderated sociological view serves as a valuable guide to understanding the social background of technoscientific research, which retains both as being recognizable to their practitioners. Because this study concentrates on the epistemological and methodological viewpoints underlining scientists' work, the speculations about the social and psychological factors shaping epistemology, for example, are mostly outside of the focus.

The social is apparently intertwined with the cognitive in learning (Vygotsky 1962). Our action has meanings within a social context, and categories of communication (or kind of inter-subjectivity) arise from that: both individual conceptual understanding and the development of conceptual systems in societies are primarily social processes (Vygotsky 1962).[14] Thus, in the education of young scientists, taking place in the hands-on building of new scientific knowledge, the two aspects of constructivism

12 Such a view promote, for example, Hacking (1983, 1999), Kitcher (2001, 2011), Machamer & Osbeck (2004), Nickles (1989) and Rothbart (2007).

13 Also highly qualified scientists have been seen to sometimes skew their research in ways favourable to their sponsors (Rochon et al. 1994; Stelfox et al. 1998).

14 The constructivist as the favoured psychological viewpoint in education, originates in Jean Piaget's account of children learning and in the stress Vygotsky placed on the importance of language and community in understanding science through an individual construction process (see Matthews 1998).

– constructivism as an educational and constructivism as an epistemological idea meet[15] in an interesting way: the socially accepted rules of epistemic action in the field in question define the culture in which the young scientists are enculturated.

2.2 ENCULTURATION IN A RESEARCH FIELD AS LEARNING THE TACIT RULES

The enculturation into scientific practices, methodologies and the community of researchers has been typically approached from the sociological viewpoint[16], but the philosophical and cognitive sides should be considered for education as well. The understanding about the basic epistemological processes of science is especially worthy in support of learning in the apprentice-master settings of research education. In such settings young researchers are expected to reach a high level of expertise, namely to acquire an ability to maintain, interpret and develop research practices (cf. Lave & Wenger 1991; Wenger 1998), by working in a research group. In the practices of research groups, research objectives naturally often over-ride the educational ones (Article IV; cf. Austin 2002; Lovitts 2004; Nyquist et al. 1999; Wulff et al. 2004). To enable working for a group, the young scientists adopt a fixed set of methods, but the justification of which is rarely addressed (cf. Grüne-Yanoff 2014). In educational research, the research groups in which natural scientists learn to do research by working with experts and other apprentices, has often been referred to or even been imitated in order to organize authentic, constructive and socially motivating contexts for learning (e.g., Boyle & Boice 1998; Gardner 2008); for example it has served in developing discovery, inquiry, problem-based and hand-on-mind-on approaches. Nevertheless, there is a lack of studies analysing the content of expertise learned in such original settings *in research groups* and how learning could be supported there. For developing education toward such objectives, in addition to the functional views about science and learning to do science, we need to understand "expertise" as a learning objective.

2.2.1 Excelling Develops through Practise

Expertise has been studied in numerous contexts – from engineering to art – and from different perspectives, most from the viewpoints of psychology, psychometry and education, but also by means of sociological and recently even philosophical studies on science (Article IV; see the references therein). Due to the contextualized nature of expertise, a variety of studies have been done on expertise development in *practical* fields, such as medical doctors, nurses or judges. Irrespective of the

15 It is important to emphasize in educational literature that such constructivism as a favoured psychological viewpoint to learning (describing individuals learning in a community), differs from the philosophical or sociological constructivism concerning the assumptions about possible existence and our ability to reach reality (concerning a community or mankind interacting with the world around it).

16 For example, Austin (2002), Austin & McDaniels (2006), Boyle & Boice (1998), Evetts et al. (2006), Gardner (2008) and Merton et al. (1975).

context of the study and the viewpoint adopted, every approach to expertise seems to highlight the importance of both (hands-on) practising on authentic tasks and personal contacts with experts in the development of expertise.

Furthermore, among the psychological viewpoints, there are some which have to be noted as a background of this study. The development of expertise in an individual has been studied in psychology in terms of the improvement of cognitive skills, such as improvement of one's problem-solving ability, or as attaining a high-level capacity, requiring in turn a large organized body of domain knowledge and diverse experience. Comparative studies between apprentices and experts' problem-solving abilities have repeatedly concluded that experts differ from apprentices, by the way in which the knowledge is organized and linked in the experts' minds. Experts excel at seeing the features that apprentices cannot see and choosing the appropriate strategies.[17] Experts have more accurate self-monitoring skills than apprentices: they are more able to detect errors and evaluate the status of their own comprehension. Therefore the cognitive and metacognitive state of experts is naturally seen as the goal of education and practising in authentic contexts plays a central role in developing it.

2.2.2 Tacit Knowledge as the Heart of Contributory Expertise

Expertise is mostly understood as context-specific excelling. Contributory expertise (Collins & Evans 2007), which is something one needs in order to succeed in a domain, basically rests on the knowledge and skills developed anyway through diverse experience in the field; evidence for the connections between the breadth of experience and performance, for example, have been found (Sonnentag et al. 2006). Overall, such an expert's knowledge includes factual knowledge as well as conceptual, procedural and metacognitional understanding, which (s)he synthesizes and then merges with skills for successful action (cf. Schon 1983 and the taxonomy of knowledge as learning objective by Anderson & Krathwohl 2001). A further important part of the contributory expertise young scientists try to acquire is embodied in practices and never articulated: it is "tacit knowledge" guiding the successful action. When chemical physicist Michael Polanyi (1958, 1966) wrote about such tacit knowledge lying at the heart of contributory expertise, he defined it as a particular quality of an individual scientist, as personal knowledge, which cannot be made explicit: "We can know more than we can tell" (Polanyi 1966, p. 4). Such tacit knowledge is naturally more complex than a sensomotoric-skill, such as riding a bike and driving car, or using a language fluently, which are favoured examples of tacit knowledge.

Basically, there are two kinds of tacit aspects in scientists' expertise. Firstly, when a scientist reaches the higher levels of expertise (cf. Chi 2006; Dreyfus & Dreyfus 1986), deep tacit understanding guides her/his intuitive grasp of situations and (s)he no longer considers the basics. The development toward an intuitive mode of reasoning is necessary for experts' effective practices (Dreyfus & Dreyfus 1986;

17 For example, Ackerman & Beyer 2006; Chi (2006), Eteläpelto (1993), Larkin et al. (1980), Snyder (2000), Sonnentag (1995), Sonnentag et al. (2006) and Verkoeijen et al. (2004).

Kimball & Holyok 2000), but before being able to develop them, apprentices need explicit rules to be able to act and then follow these rules. Thus there is a tacit component which may have been (or at least could have been) learned as explicit knowledge after which it becomes tacit.[18] Secondly, at the heart of expertise lies a tacit understanding based on successful epistemological and methodological ideas, which is embodied in practices. It guides knowledge construction and justification practices together with understanding the different interpretations of these practices. It also develops through success achieved in practice and thus is never made explicit. Numerous famous examples can be found in the history of physics how certain adopted philosophical viewpoints have guided physicists to success, and how other viewpoints have prevented other physicists from interpreting observations in ways which were later established as the best scientific explanations (see e.g., Chang 2004; Darrigol 2000).

Nowadays, tacit knowledge (of both kinds) is discussed as something which a group of experts share and which can be (partly) revealed through careful analysis carried out in interdisciplinary cooperation (Collins & Sanders 2007; Collins 2010).[19] With this objective to develop the field in mind, organized communities of practice (Lave & Wenger 1991) are effective mechanisms for developing tacit knowledge (Lesser & Storck 2001; Wenger & Snyder 2000; Wenger 1998). In science, such sharing and developing of tacit knowledge typically means working on shared objectives, methods, instruments and objects. In that the cognitive excelling can be seen to be located not just in individual minds, but rather within a complex, distributed system of people, representations and machines (cf. Hutchin 1995). In this way the apprentices develop their epistemic identity (Osbeck et al. 2010), based on an ability to act in the particular epistemic culture and finally develop it further. What learning in such a wide apprentice-master systems means, and how it could be improved, has been previously discussed in other contexts, due to the education of practitioners.[20]

As a consequence, the challenge of learning in an apprentice-master system is not that the experts would like to hide something, but that part of the knowledge that young scientists are in the process of gaining is *unrecognized* and not explicitly discussed in the research groups. The potential to contribute to the development of expertise on the basis for the explicit analysis of experts' tacit knowledge has been advocated by a number of scholars (Argyris 1993; Brown & Duguid 1991; Cianciolo et al. 2006; Schon 1983). In this dissertation, such analysis is developed through a collaboration between practising scientists and researchers in education and philosophy (see section 3).

18 Part of such knowledge is transferred (and may also originally developed) as uncognized (or even uncognizable) knowledge, which is passed on only through apprenticeship and unconscious emulation (Collins & Evans 2007).

19 Here is assumed that, by interdisciplinary co-operation, we *can* make explicit at least part of such tacit knowledge which *is not* typically made explicit in research groups. Thus, the term "can" in Polanyi's citation is not understood as a scientific or logical impossibility, but as a situation which can be improved (see Collins 2010).

20 For example, Ainley & Rainbird (1999), Cate & Durning (2007), Gamble (2001), Gardner (2008), Laudel & Gläser (2008) and Nersessian et al. (2003).

3. RESEARCH APPROACH

This study focuses on knowledge construction and justification in physics as learning objectives, paying especial attention to the role of technology. Such a naturalistic approach (see Rosenberg 1996) is adopted here, where close co-operation with practising scientists or case studies addressing these practices plays a central role. The adopted attitude is thus to study science as it is, not what philosophy of science may (normatively) state it should be. Such an approach is widely used in recent philosophy and sociology of science which pursue practical consequences[21], because it opens up wider viewpoints than could be derived from what we know on the basis of general philosophy of science or what we know about the general properties of the human mind. In this way philosophy and history of science can serve the function of investigating scientific questions that are not often addressed in current specialist science for the necessities of specialization: as its aims are continuous with the aims of science itself, it is kind of continuation of science by other means (Chang 1999; Nagatsu 2013; Ross 2014). Yet the means and methods employed in constructing such authentic cases vary a lot and have to be developed. The co-operative analysis of scientific practices increases methodological self-awareness among scientists (cf. Collins & Sanders 2007), and such understanding about science is valuable also for philosophy and science education (e.g., Ankeny et al. 2011; Goldman 1992; Matthews 1994; Grüne-Yanof 2014). Physics education research, performed in the department of physics with close relationships to researchers in both education and philosophy, provides a fruitful place developing the means to study and for studying the practising scientists' viewpoints to science for science education.

Research developing deep viewpoints on complex phenomena requires employing multiple levels of analysis. Thus, the study combines a theoretical approach with empirical means in order to reveal epistemological, methodological and cognitive aspects of doing physics that practising physicists can also agree with. Indeed, by using two or more complementary approaches in the study of some aspect of human behaviour a kind of methodological triangulation can be reached (Cohen et al. 2000; Flick 2007), which builds confidence in the validity of the results and conclusions (Flick 2007; Johnson & Christen 2004). While the theoretical part of the study develops at quite an abstract level, the empirical part studies the phenomenon in the contexts of present, actual practices. In consequence, the adopted naturalistic approach to scientific knowledge construction combines philosophical, educational and scientific viewpoints and methods in order to attune its authenticity.

21 In the field of education, the adopted empirical approach can also be called naturalistic inquiry (Cohen et al. 2000) or ethnographic research (Nersessian et al. 2003).

3.1. RESEARCH PROBLEM

This dissertation scrutinizes how technology shapes and ultimately configures the epistemology and methodology of experimentation and modelling – and what kind of expertise is developed in such technoscientific practices. The new views on knowledge-building are developed primarily by theoretical means in the contexts of the methods where technology plays an obvious role: experimentation and modelling. The theoretical ideas are then tested and deepened in an empirical context of nanomodelling practices, in co-operation with researchers of the field. In consequence, the research questions took a broad perspective on the nature of physics, but aim also at revealing deep viewpoints on the issue in the selected contexts. The research questions are

1. How is physics knowledge construction and justification shaped by technology through a) experimentation and b) modelling?
2. What views of models and modelling and their relations to theory, experimentation and reality guide knowledge construction in nanophysics?
3. What kind of expertise do apprentice nanomodellers acquire by working in a research group?

Each research question naturally divides into more detailed questions (as presented in Articles). The first research question is the broadest one establishing the basis for the others (together with the further studies). The technological nature of physical knowledge construction is discussed in Article I, mostly from the viewpoint of experimentation (Question 1a), whereas Article II discusses how the conceptions of models and modelling (1b) are to be extended in the era when computer technology opens up new possibilities. Nanophysics constitutes a technoscientific field and is thus a natural place to test the new ideas. The second research question takes then a closer look at ideas underlining knowledge construction on such an interdisciplinary field (Article III, Question 2). In the field of education, a question that arises is how and what kind of expertise is learned in such a field: the third research question is focused by Article IV.

3.2 EMPIRICAL TEST OF NEW THEORETICAL VIEWPOINTS

The empirical study follows a common “paradigm case” method in philosophy: to understand something, find an exemplary instance of it and examine its features and ramifications. The limitations of such an approach are well known (e.g., Lakatos 1971; Watkins 1957) and those concerns all the philosophical interpretations of history or recent cases. Thus, it is only important to note that the understanding constructed in this study is not claimed to be “absolutely true” in any sense, but instead the objective is to develop functional viewpoints in co-operation with practitioners of science, to be used in understanding the scientific practises from the inner viewpoint and for science education. From the viewpoint of the objectives of this study, there is no reason to try to achieve a more objective picture of science than what the practitioners can achieve by supported reflection.

Thus, the empirical part is essentially a case study. To a certain extent, the selected group of scientists can be understood as informants of the research culture of their field (computational physics and material science) and its ways of thinking and acting, like the members of a tribe in anthropological or ethnographic research (e.g., LeCompte & Goetz 1993).[22] Such ethnographic field-work is increasingly used also the studies among scientists and engineers.[23] By comparing the individual responses and asking the interviewees to comment upon the analysis, an understanding can be reached about the views shared among these practising scientists.[24]

Such a case study can even address the issues of generalizability – a tenet of positivistic research – interpreted as 'contrability' and 'translatability', if the characters of the individuals and the group are made explicit (Cohen et al. 2000). The informants are the Finnish material physicists studying nanophenomena by "realistic simulation": five experts (E) and five apprentices (A) (for the more detailed background of the researchers, see Article III). Each apprentice works for a different project of an expert: then they all model different nanophenomena in different materials with shared method(s), mainly by way of computer code developed in the group. The informants constitute a flexible group of computational physics in material sciences. If compared with other research groups from a worldwide perspective, the Finnish nanoresearch group is a rather small and flexible one. On the one hand, new ideas and views can be easily discussed and quickly reacted to on such a small scale of communication and, on the other hand, there is active co-operation with other groups, because it is vital for such a small group. For example, the experimental counterparts of the simulations of the interviewees come mostly through international interaction. Thus, the informants work in international co-operative efforts. Moreover, the previous apprentices, who had already left the group in which most of the interviewees were working, had found good employment in their field and also outside of it. Thus, we have good reasons to assume that at least the other physicists studying nanophenomena through "realistic simulations" (described in section 5) have similar viewpoints about the basis of their field as the ones emerging in the study. Furthermore, expertise nurtured in simulative modelling in other fields can be assumed to varying degrees to have a parallel character.

22 The approach differs from the anthropological and sociological ethnographic studies on laboratory life (see Latour & Woolgar 1986) especially in that the researcher(s) are familiar with the institutional culture and informants' research practises and the informants agree with the researcher(s) of the benefits of the study (cf. Metcalf 2002).

23 For example, Bucciarelli (1994), Latour & Woolgar (1986), Nersessian et al. (2003), Pickering (1995), and see also Bernard et al. (1984).

24 PhD students work as apprentices in the research groups in order to reach the expertise nurtured in such groups; in this sense the more experienced scientists' (experts') viewpoint on the issue serves them as an objective of learning (see the section 2.2) – the standpoint which the apprentices aim to reach in order to develop it further.

3.3 CONTEXTUALIZED QUESTIONNAIRE AND INTERVIEW AS RESEARCH METHODS

The attitude toward the use of methods is instrumental: methodology is not the starting point or primary goal of inquiry, but instead the methods are tailored with the objective of producing functional understanding of the phenomenon under study as explained more deeply in what follows. The contextualized questionnaire and interview are developed and employed as research methods in order to identify the epistemology and methodology addressed in nanomodelling practices as genuinely as possible. This method is employed as a way to sketch the expertise young researchers are supposed to achieve by participating. As a research method, interview provides access to what is "inside a person's head" (Tuckman 1972). This study aims a bit further in any case, by encouraging the interviewees to reflect on the basis of their thinking and acting[25] and then asking them to articulate this reflection in the questionnaire and in the interview that follows. In this way, a deeper view is reached than would occur in plainly asking them their views about science: interviewees are experts – or becoming experts – in science, not in philosophy, and thus they supposedly have not analysed their action from the viewpoints considered in this study. While the empirical study focuses on *scientists' shared perspectives* on their knowledge building practices and learning those (cf. Nersessian et al. 2003), it admit the social nature of scientific enterprise (section 2.1.4).

The empirical part employed the two methods on every informant separately: a questionnaire and a focused interview which deepened the responses (see Figure 2).

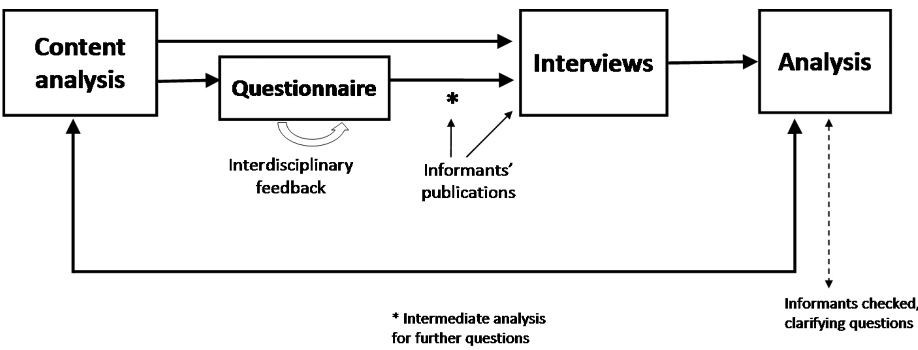

Figure 2: The research process.

25 By asking reflective questions, the informants are supported in reflecting on the shared basis of their action (cf. Kompf & Bond 1995; Kreme-Hayon 1988), namely the tacit knowledge embodied in their practises and expertise (cf. Collins & Evans 2007; Collins 2010; Polanyi 1958, 1966). The meaning of "reflection" is understood as it comes near the verbs introspect, echo, consider, examine, inspect, investigate, explore, study, look into, analyse, interrogate, and scrutinize (Kompf & Bond 1995).

Such a structure provided the interviewer, on the one hand, with the possibility to clarify her understanding and interpretation of the responses. On the other hand, when responding to the questionnaire was a prerequisite for the interview, the questionnaire launched the reflective process: the interviewees' understanding of the basis of their action and communication of it was further developed in their reflective thinking for the interviews, which were performed about a week after they responded to the questionnaire. Indeed, the written and oral forms of responding support different learners in different ways: some prefer to reflect by writing and others by speaking (cf. Cohen et al. 2000; Kolb 1984; Manolis et al. 2013).

The design of the **questionnaire** (see Article III) – and interviews – was guided by content analysis (see sections 2 and 4). The content analysis identified the major areas of enquiry and the hypotheses, which determine the relevant data to be obtained (Merton & Kendall 1946). Indeed, the questionnaire was further developed on the basis of discussions with researchers in physics, philosophy and education to reduce the level of ambiguity. In this way the epistemologically central questions were transformed in the series of questions relevant to practising scientists. As a result, responding to the questionnaire required quite hard work, which could lead to a low response rate. Nevertheless, every scientist in the aforementioned group accepted the invitation and participated actively, one reason for which was their interest in improving enculturation into the field.

A central idea guiding the design of the empirical part is "authenticity", which is aspired to through contextualization[26]: the theoretical viewpoints were studied as contextualized in the interviewees' actual research projects and practises, the basis of which provides the study's main focus.[27] The viewpoints natural to practising scientists guide considerations as to what these scientists actually do, how and why they do them when building new knowledge together with developing methods (instead of asking them to generalize in philosophical terms). The contextualization of the central epistemological questions was guided by understanding of the modelling practises in physics on the basis of both theoretical analysis of scientific practises and familiarity with the research culture in the field. In such an approach, general questions - such as "how is knowledge justified in science?" - are primarily transformed into the form relevant to the practising scientists, such as "how do you make your colleagues believe that this model/idea/tool you have developed

26 This kind of study can naturally be mined merely to find support for the selected epistemological positions as justly presented often when discussing Kuhnian interpretations of history (see Lakatos 1971), but this kind of chicken-and-egg problem concerns all the philosophical or historical interpretations of scientific cases (Matthews et al. 2004). Here the fallacy is went against by contextualization and on-going interaction between the researcher(s) and the informants in producing authentic understanding. There is no reason to reach more objective picture of science for science education than the practitioners can reach by reflection.

27 In comparison, the favoured questionnaires aspiring to construct picture of the nature of science for science education, asks, for example, 'What is an experiment?' (VNOS-C) or 'what is the difference between scientific law and theory?' (VNOS-B&C). Then practise-oriented view introduced in this thesis elucidates 'what scientists actually do when constructing and using the methods and tools', 'what is the benefit of different activities' or 'what a scientist actually do when (s)he aim to convince peers about functioning of a certain model, experiment or idea' and 'what skills a novice scientist have to reach in order to do that'.

is good/functional for its intended usage?" By contextualization it was possible to avoid the situation where the informants would respond on the basis of the general (philosophical) ideas they had explicitly learned about science, or would like to tell the public, rather than reflecting on the actual ideas underlining their recent practices. The contextualization was supported by asking the interviewers to attach three of their best publications to their responses. Part of them also provided visualizations of their simulations, which they use in communicating and working. This kind of "naturally occurring empirical data" supporting and sustaining communication and intellectual work (Nersessian et al. 2003) have a direct connection with the very object investigated; thus, employing it in the interviews is said to increase the reliability (Peräkylä & Ruusuvuori 2005; Silverman 2006).

The **semi-structured interviews** were designed on the basis of the informants' responses to the questionnaire, on the articles they sent with the responses together with the content analysis. Each informant explained his own responses in the interviews (validity, see Miles & Huberman 1994). To further maintain the validity of research, a certain level of openness was left in the protocol, so that whenever it was relevant, the interviewer could ask further or deeper questions of the interviewee. Indeed, the contextualized approach encouraged the use of popular language and language used in physics, instead of purely philosophical terms (securing validity in communication). The interviews (for details, see Articles III & IV) were taped and transcribed. Some clarifying questions were asked afterwards by email (validity of communication/interpretation).

3.4 ANALYSIS OF THE EMPIRICAL DATA

The aims of this study resemble the phenomenographic approach (Marton et al. 1997; Marton 1981; see also Ekebland 1997), while focusing on individuals' and shared interpretations of their thinking and acting.[28] The interviewer is recognized as one of the interpreters, co-constituting the reality under study, although the interviewer aims to reveal what is within the minds of the interviewees, as uncoloured and unaffected by the interviewer. In phenomenographical analysis, categorization is often based on the research data (Marton et al. 1997). Because the aim of this study, in any case, is to produce results comparable with the theoretical part of the study, the categorization of the data is here, to a large degree, based on preconceived criteria embodied already in the design of the questionnaire and interviews; otherwise, it follows the procedures of the phenomenographic analysis.

The data gained from the questionnaires and interviews were analysed by means of qualitative content analysis (Cohen et al. 2000; Patton 1990; Rubin & Rubin

28 A phenomenographical approach seeks a description and understanding of experiences (Marton 1981). The object of this phenomenographic study is thus not the phenomenon per se but the relationship between the actors and the phenomenon. This is the "second order" viewpoint (Marton 1981), which differs from the positivistic view of "first order" in that it emphasizes the role of social construction in attempts to understand the world and everything in it.

1995), in which the responses to the questionnaire and interview questions of each informant were scrutinized as a whole; the purpose of the various questions in the questionnaire and interviews being simply to make the respondents talk about the issues from various angles and in different contexts. The analysis focused on the modelling activity and its relation to experiment and theory and, indeed, on expertise developed in such a context (for detailed questions guiding analysis, see Articles III and IV). At every stage of the research process the role of technology and technological capability in the process was scrutinized. Phenomenography tries to produce a description which characterizes different conceptions and to explore relationships and differences both within and between these conceptions. In data analysis, the similarities and differences are explored across rather than within the person's responses. Especially attention was paid to the differences between apprentices' and experts' views. Indeed, where differences were found in the analysis between the apprentices' views or experts' views, the background – working years in the field, nature of previous experience etc. – were considered. The analysis concentrates on describing the similarities interpreted as the shared epistemological views.

In consequence, the research is carried out by starting with the developed theoretical ideas (section 4; Articles I & II), which are then tested and deepened by discussion about the empirical study among nanomodellers (5; III). Finally, the nature of expertise young scientists are achieving by working in such an evidently technoscientific field is discussed (6; IV). After summarizing, the section 7 briefly discusses how the appropriateness and truthfulness (cf. validity and reliability) were reached by empirical study, while section 8 develops implications or applications for education.

4. TECHNOSCIENTIFIC KNOWLEDGE-BUILDING

Because the experimental testing of abstract ideas is the foundation of physics and chemistry, the question as to how the theories fit with experimental reality is central from the point of view of both studying science and understanding science for education. When considered from the analytical point of view of SVT (see section 2.1.1), the process of theorizing through experimental action in man-made laboratories is seen to take place in the hierarchy of models constituting the knowledge of science. The central question is thus how similarity (Giere 1988, 1999) or empirical adequacy (van Fraassen 1980) between the models of lower levels and the experimental world[29] is to be reached. The semantic views do not answer this question. In terms of models, the situation is easier to understand if one adds **material models** to the hierarchy, at its lowest levels. Namely, experimental set-ups and devices can be seen as the concrete material models, which carry the "thing knowledge" (Baird 2004) – knowledge about designs, materials and practical conditions needed to complete successful experiments. The advantage of the material models is that they can be manipulated materially and thus they provide a different entry to the world than conceptual and visual models. Apparent historical examples of scientific material models are the "ball and stick" models of chemistry or Watson's and Crick's DNA model, which embody the knowledge extracted both from experimental results and theory, but in fact most laboratory phenomena can be seen as a kind of model of something outside the laboratory.

The machines used to construct the phenomena or conditions in the experimental system, such as Robert Boyles's air pump, cyclotrons and particle accelerators, are material models of both functional and structural ideas and principles underlining the system. In addition, measurement instruments can be considered as material models, of which ability to produce the material values of theoretical measurements is based on the theoretical understanding embodied in their development (for an example, see Chang 2004; Middleton 1964). Moreover, the development of the material models is tied to our capacity to construct, control and manipulate "the world in laboratories" and thus the knowledge embodied in material models is at least partly technological, including the knowledge that Davis Baird (2004) calls "working knowledge". The experimental machines or settings create the phenomenon to be tailored in the laboratory and measurement instruments are material models with an ability to control the material (theoretically expected) values of measurements. It is through the material models that the concepts of theories acquire their empirical meanings. On the one hand, the great use of the material models is their ability to function as basic models which can be used to reduce complex real phenomena into analysable and understandable parts. On the other hand, the laws of physics

29 To be exact, for Bas van Fraassen (1980), the similarity or isomorphism that we try to reach is between theoretical models and data models.

can be supposed to apply only where its models fit, that, apparently includes only a very limited range of circumstances (cf. Cartwright 1999a). As a consequence, through providing both **scaffoldings and limits** of physical reality accessible to us, technology also necessarily affects our conception of reality. Section 4.1 considers how technological nature figures out knowledge-building and its products.

It is often the computer modelling and simulations (running models on computers), which function as an active link between conceptual and material models, thereby fitting those together. It is the active, creative role in constructing new reality, which differentiates the new computer simulations from the earlier analogical and material models, including the ship models and wind tunnels as well as the nineteenth-century models built out of pulleys, springs, and rotors to recreate the relations embodied in electromagnetism.[30] That is why, in many areas of physics, computer modelling has opened new possibilities for generative knowledge-building. Modelling in the virtual world is free of the limitations of both material reality – laboratory experiment is never an idealized situation – and complex theoretical structures. After all, the developing control over phenomena in the virtual world embodies a huge amount of new kind of technological understanding. How the fit between the computer and the material models, on the one hand, and between the computer models and theoretical models, on the other, is developed and estimated, are the epistemologically central questions. These issues are considered in what follows, firstly at the more general level (section 4.2) and secondly in terms of the empirical case study (5). In consequence, the hierarchy of developing models (Giere 1988, 1999) is here extended to run from material models with "thing knowledge" (cf. Baird 2004; Tala 2013b), to the numerical and visual ones manipulated by computers, and through the stages of more general experimental and theoretical models, to finally reach the models of the highest levels of theory.

4.1 PHYSICS AS CREATING AND REVEALING THE WORLD TECHNOLOGICALLY

Not only engineers create things (technical artefacts), but also scientists create things: they create phenomena by using the scientific instruments of very special design towards that purpose (cf. Hacking 1983). In the experimentation of physics, the world is simultaneously written and read technologically at least in two senses. Firstly, increasingly more scientific phenomena are clearly technologically produced and tailored. In experimental laboratories we do not see scientists "observing" nature, but instead we see them actively and intentionally creating and designing material models, namely experimental settings, instruments and machines, which produce or isolate interesting phenomena, which do not exist outside the instruments and machines as such. The phenomena studied in experiments are "**laboratory phenomena**".

30 Previously, modelling and simulations referred to the use of electrical and electronic analogue devices designed to mimic the behavior of real-world phenomena. It was the introduction of the digital computer that provided the major impetus for the adoption of simulation techniques in scientific research (Galison 1997), while making it possible to include creative components in modelling.

Secondly, physics is instrumentally revealed and even produced. The experimental data are not collected by passive observations but detected by **theory-laden instruments**, the “in-built intention” (Ihde 1979), of which is to reduce and modify the complex phenomena to particular quantities. Moreover, in the matchmaking between theoretical and empirical realities in the virtual world, scientific reality is literally built in the artificial world, which finally embody both the conceptual understanding and material control over the phenomenon. As a consequence, science discovers through producing artefacts – material, virtual as well as conceptual models. This, on the other hand, creates the knowledge of physics in a special form of quantities and laws, a very special product of experimental process made possible by the instruments and machines made for that purpose in technoscientific design.

4.1.1 Technoscientific Design at the Heart of Science

In the knowledge construction through experimentation the abstract, inaccurate, ideas and concepts describing “the world” are defined and developed, by designing and using instruments and experimental settings, which have the purpose of making the concepts mutually measurable and materially controllable (for examples, see Chang 2004; Middleton 1964). The central “method” of physics is, in practice, centred in **technoscientific design**, which **is a cyclic and iterative process**, providing creative and critical planning and construction of material experiments, using and developing knowledge of experimental technology and scientifically designed experimental knowledge (Article I). This process intertwines the development of science intimately with the development of technology, considered both as knowledge and action (Figure 3).

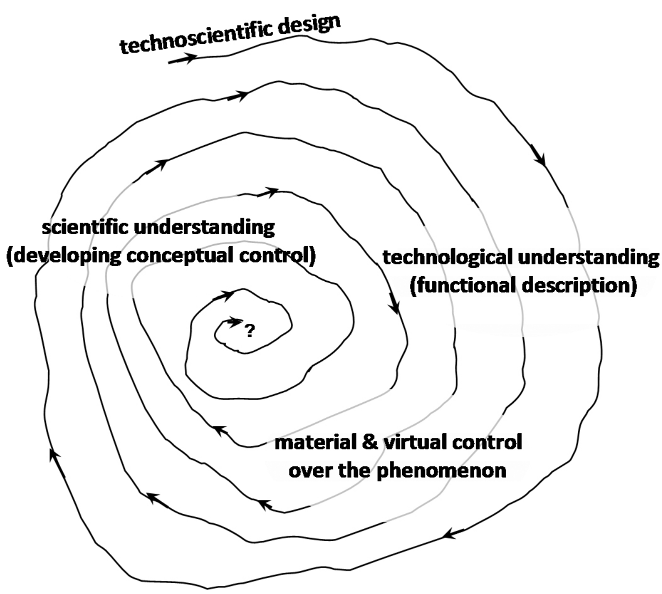

Figure 3: Technoscientific design cycle.

Technoscientific design follows primarily a practical logic: the materialization of the idea, being functional, is worth developing further. As a result, the designed material models of scientists' ideas of physical reality carry knowledge about design, materials and practical conditions needed to construct them or complete successful experiments, namely the technical know-how and functional rules needed for experimental success, for example. Indeed, the possibility to produce generizable knowledge in such a process lies in the theoretical framework of the design process. Recent empirical studies have scrutinized this kind of mixed mode of understanding in the field of engineering (see section 2.1.1), but it is worth considering also in technoscientific design in the context of science.

An ability to employ technological devices also in scientific research – consider, for example, the complete understanding of the tunnelling microscope or barometer (in Middleton 1964; Rothbart 2007) – requires both functional and structural descriptions and ability at different levels (cf. Baird 2004), which at the same time are rooted in physics and technology. Simply, without the means of intervention, without a suitable device and machines, there is no prospect for demonstrating success. The scientific ideas are often primarily present in experimenters' skilful practices, communicated by a visual language and developed in design plans and experimental inquiry, which prepare scientists for action. Such ideas about idealised relationships between experimenters, instruments and laboratory phenomena in various conditions, can then be read in design plans (see Rothbart 2003) and in laboratory notebooks and sketches of experimental settings (see pictures for example in Darrigol (2000) or other reprints of the original ones), which transforms the ideas in the form of diagrammatic reasoning.[31]

Technology being an enterprise concentrating on doing, also the "tacit knowledge" may be easier to recognize when considering the technological nature of science: Successful realization of experimentation and design requires special knowledge and training in special experimental techniques. In the context of science, the case of the TEA laser is often taken as a classic example of how the tacit knowledge (in this case mainly procedural) needed for experimental success cannot be transferred from one place to other through the scientific literature alone; instead, they needed the concrete experience gained through visiting in the group to be able to build it.[32] In this particular case, the successful transfer of "tacit knowledge" necessitated personal contact with an accomplished practitioner, and as the knowledge was "invisible" the scientists and engineers did not know whether they had the appropriate ability to build a laser until they tried (see Collins 1985). Another example of the transfer of procedural skills is the historical way of guaranteeing the success of the replication of an experiment by sending material models, such as "Faraday's motors" demonstrating electromagnetism or the electric coils William Thomson sent

31 For diagrammatic reasoning as a tool, see (Anderson et al. 2002).

32 Naturally, also the scientists having the tacit knowledge have to be willing to not to hide part of it (for detailed examples, see Collins 1985).

as part of his measurement of ohm (Baird 2004). Methodological tacit knowledge[33] is naturally needed for success when using other methodological approaches as well, like modelling or theoretical ones.

In sum, every method, every experimental system, instrument or specimen or in a computer coded model or model environment finally embodies the experimenters' and modellers' epistemic and methodological ideas, of which material models they are. A product of technoscientific design is not only an understanding of some physical phenomena in the particular case, but also necessitates and provides the capability to create phenomena and design ways to control and manipulate them. The design work aims to develop methods as well as individual claims, which finally become practically and socially justified in the iterative process: the justification of the designed experimental systems and instruments lies in the **pragmatic**, scientific determination that they work. Consider for example the evolving understanding of "pressure" and "temperature", which took place in mutual interaction by the development of instruments such as thermoscopes, thermometers and barometers (Chang 2004; Middleton 1964). In this way, physical reality is seen as the outcome of a technoscientific practice, not only as its object. When considering such a design of physical reality, a naturally arising question is what then, is physics about, if it is seen as constructed by studying man-made laboratory phenomena?

4.1.2 What Is Science about?

The phenomena under study are "created" in two senses: On the one hand, the materialization of the experiment is the creation and manipulation of an apparatus producing or isolating phenomena and instruments reducing and modifying those to experimental data. On the other hand, the simultaneous conceptualization of nature takes place in the mind of the intentional researcher by his or her own cognitive acts; it is neither produced by the object of manipulation, nor does it arise directly from the object of "Nature". Facing the creative and intentional nature of knowledge construction encourages reconsidering the traditional conception of physics as describing independent, constant features and causal regularities of "Nature". In full-fledged constructivism, such notions have led to views, according to which the experimental objects and processes are nothing but artefacts produced by the negotiation processes between the actors involved and science thus as a whole is a branch of technology (see Article I and section 2.1.4). Because the viewpoint promoted here is that of scientists, the notion of the strong creation of physical reality does not imply subjectivism or relativism. It is natural that the experimental systems are designed to produce the intended effects. Moreover, in increasingly many cases, some of these actions are substituted by creative computer modelling, where scientific understanding arises in a thoroughly artificial, virtual system. Nevertheless, experimenters cannot create phenomena and develop instruments according of their own free will (cf. Hacking 1983), but they experience a number

33 Such methodological knowledge is partly "weak" in the sense that at least part of it could in principle be made explicit. It is also closely linked to collective tacit knowledge. (cf. Collins 2010)

of constraints when intervening in the world: technological, economical, political, ethical, and social – among other constraints, which are linked to us as human beings – that change over time. The scientific constraints limiting the experimental systems are assumed to differ from technological constraints in such an essential way that they cannot be overcome, not even in the ideal picture where every scientist would have unlimited research resources. From another perspective, contemporary scientists are frequently asked how their research can be applied to technological development (see Article III). The drive for applications harms basic research, but can support scientific progress as considered from the viewpoint of epistemology: it is not possible to explain the successful improvement of design on the basis of only socially constructed knowledge conditioned by structures and the interests of actors.

At the other extreme, we find views which are based on a strict separation between the natural and the artificial in experiments. For most of the earlier approaches[34] to "the growth of scientific knowledge" the instruments are the "transparent" means by which to produce the facts of nature. This view, based on the assumption that it is always possible in experimental results to eliminate (at least nearly) all that is artificial, cannot be supported in the face of the actual practises of physics.[35] Nevertheless, such notions can guide us in re-considering what scientific knowledge designed in the technoscientific process is really about. For example, what aspects of "natural" phenomena are we studying when we study the interaction between short-lived entities produced by particle accelerators or nanomachines, which do not exist outside of laboratories? What do we "see" through an electron or scanning tunnelling microscope or sonic probing? What do we achieve by employing measurement instruments, such as thermometers and voltmeters, producing quantities, which are not properties of nature as such, but rather what have been called "phenomenological profiles" (Ihde 1979) of instruments? Or, what really is constructed when studying nanophenomena in virtual systems?

What seems to be certain from the ontological viewpoint, is that physics itself cannot distinguish between the artefactual and the natural (Kroes 2003), since all objects are physical and cannot be studied without intentional action and inference. Nevertheless, the question regarding the back-inference from laboratory-phenomena to the world outside laboratories is important for physicists. From the material point of view, part of the laboratory phenomena studied are completely non-natural, in the sense that they do not occur spontaneously or without human intervention, for example the Hall effect, W-bosons, pure chemicals, nanomachines and, from earlier history, Andrew Crosse's "electrical life". "More natural" phenomena are also

34 This was characteristic, for example, in discussions between inductivists, such as John Stuart Mill and William Whewell, and fallibilists and provisionalists, such as Francis Bacon and Karl Popper, who see experimentation as a pure means of producing particular empirical propositions by which the epistemic value of general, theoretical notions are to be assessed.

35 While experimenters anyway speak about artificial data, as opposed to genuine data, they refer to the data produced by the features of the material model extending the ideal situation; such as the famous coloured fringes which the early telescopes produced due to chromatic aberration, the "noise" of the data produced by telescopes or the measurement instrument's unintended impact on the state of the system.

constructed in laboratories. These phenomena are somehow “tamed” and reduced from the world outside the laboratories in their entirety. Examples of these can be found in the mimetic experiments of the 18th century (see Galison & Assmus 1989; Hackmann 1989; Article I) as well as samples in ice laboratories. Also subatomic apparatuses of the 20th century (see Bohr 1958), engage in such a “taming” process in a partial manner. Even the research stations measuring values for simulations of relationship of atmosphere and forest participate in such “taming”. Moreover, what is detected (instead of ‘observed’) in experiments is figured out by theory-laden technology. Finally, only the similarity between certain features of the prediction of a conceptual model as interpreted at the material level and the certain observable features of the outcomes of running a material model or measurements, can be fitted through experimentation and modelling (Articles I & III). This comparison is the basis of construction and justification for the “natural laws” in physical reality. On such a technoscientific view, technological devices and the phenomena they produce are also part of physical research and of scientific interest, and on the broader scale, also part of nature.

As a consequence, while physics is telling us only about how we can interact with and control the physical world, it is not necessarily informing us about constant causal conjunctions of actually occurring, natural events (cf. Humean regularity theory).[36] What experimental **laws of physics describe is potentiality**, potential causality (Woodward 2003) or potential statistical regularity.[37] We cannot expect those regularities to occur spontaneously or expect that they have been waiting there to be discovered, without human intentional action. Finally, the instrumentariums and the associated know-how, on which the physical laws are based, define the degree to which the empirical adequacy or reliability of knowledge can be extended – and the limits of the application. Physical ideas cannot reach any deeper empirical adequacy than provided by the instrumental view to knowledge.[38] In this way, physicists may “motivationally” (Fine 1986) agree with Heidegger’s (1927) idea that even the most theoretical heart of science is a product of a technological way of being in the world.

4.1.3 Iterative Design of Reality

For the vitality of science, the very success of the experiments lies in the control and manipulation of material laboratory phenomena, which is somehow independent of the theoretical interpretations (Hacking 1983). Obviously independent of theory development was the development of optics between the 17th and 19th centuries based

36 Thus, for example, the logical empiricist account that physical laws are universal and true generalizations, promoted in science education, is too broad from the viewpoint of the practises of physics (see Article I, cf. II & III).

37 cf. Nancy Cartwright’s (1999a) suggestion to consider scientific knowledge rather as knowledge of capacities than knowledge of laws.

38 Following the instrumental theory of Dewey (1916) all knowledge, even the most esoteric theoretical concepts from the most uncommon fields of research, has meaning only to the extent that it provides a means to some end. Instrumentalists came to regard theories neither true nor false but rather as instruments of prediction (e.g., Hacking 1983; Lakatos 1971), which may is the limit of the physicists’ empirical means.

on the practitioners' methods, for example, and the foundations of both thermometry and barometry at a time when no established theory was capable of guiding the design until the 19th century (see Chang 2004; Middleton 1964). Similar material success prior to abstract understanding can be recognized in the rapidly developing fields of research, such as nanoscience. In an experimental invention, however, certain states of affairs are intentionally brought about, which would not have arisen without the interference. Moreover, we could also have chosen to realise another state than that finally chosen (cf. Bohr 1958; Janich 1978). For example, in subatomic physics, can be provoked either particle phenomena or wave phenomena to occur, depending on which hypothesis or model the apparatus is designed to support (see Bohr 1958). Respectively, by running the original cloud chamber, one may study meteorological phenomena or elementary particles[39], depending on the theoretical framework omitted. When the cloud chamber is used to study particles, there is still 'thing knowledge' embodied in the experimental success, but the epistemic part of it does not concern cloud formation or optical phenomenon. The same applies to the transfer of methods and associated technological ability from one field to another. As a consequence, technoscientific design becomes scientifically meaningful only within the selected theoretical framework, which itself becomes revised in the iterative design processes often taking place in computer modelling, which guides both the materialization of ideas and the symbolic interpretation of them. This is how the design process combines the stage of "knowing" and "doing" into a continuum, or at least forms a stepwise sequence between the abstract level of theory and the material level of action. The medium is written in design plans of material experiments or simulations.

Also the "crucial" design of theorizing and experimenting can be explained by iterative development of independent but interactive stages of "knowing-how" and "knowing-that": physicists adopt at every moment the existing systems of "know-how" and "know-that" knowledge and existing material abilities to control experimental systems (without any firm assurance of the correctness and accurateness), and, moreover, aim to sharpen and correct them both (cf. Chang 2004). For example, in the beginning of the design process of an instrument, physicists can have assumptions about the basis of a measurement technique, which expresses the quantity to be measured (e.g. temperature or air pressure) as a function of another directly observable quantity (e.g. the height of a liquid column or the colour of a test object). The design process aims to sharpen the measuring techniques by increasing simultaneously both the understanding of the material relationship between these quantities, and the material control of the quantities (see Chang 2004; Middleton 1964). In this process, the design and interpretations of the success are nowadays often embodied in computer modelling. When scientific understanding is developed in the virtual world, the technological ability to model it (software) is thereby also developed. Furthermore, scientific progress means the crossing of limits of particular

39 For the development of the cloud chamber, see Galison & Assmus (1989).

material settings. The reproduction of the ideas in different material settings means, for example, using several methods to measure the quantity under development.[40]

The developing theoretical framework guides the connection of the understanding reached through control in different material settings. From the scientific side, it often has to be the same framework, which guided design from the very beginning: thus, the justification process can be said to result in endless regression without coming to any conclusive views (see Collins 1985; Nickles 1989; cf. MacKenzie 1989). At this point, the negotiation of the scientific community is vital (section 2.1), since it defines the rules and limits of the system in which the new knowledge is justified. Again, to state "how abstract ideas relate to the world" it is pertinent to ask "what makes certain measurements or laws of physics true?" instead of asking, for example, "how can those be used in the present conceptual and material system?". Such a question would be the impossible attempt to step outside our skins – the immediate experiences, traditions, linguistic and other, within which we act, think and self-criticise – and compare ourselves with something absolute. The technoscientific design process aiming at tightening the conceptual and material control over the physical world, is embedded in the theoretical and social framework. In this self-correction process, the concepts and laws of physics, along with the ability to measure the related quantities, are developed.

In sum, technoscientific view reveals that practising physicists have no any normative scientific method to be used in their "knowledge factory", but instead they design effective scientific means and methods together with new functional knowledge to be used in understanding how we can interact with the world around us (instrumental rationality) (Articles I, II & III; cf. Hull 1988; Laudan 1987). Such design of physical reality is an iterative process. Recent developments in computer modelling have provided the technoscientific design with new kinds of tools. In computer modelling, scientists' ideas can be tested and developed by mixing more flexibly the general ideas with understanding reached in particular material settings (see Article III). In fact, the development of knowledge-generative computer modelling substantially extends and at the same time alters the evidential basis of recent science as introduced in the following sections (by basing on Articles II, III and IV).

40 Nevertheless, by developing a variety of methods to measure a series of definitions are invented, if there is no standardise plausible procedures for measurements and for measurements and methods to compare different measurements, by developing a variety of methods with which to measure, a series of definitions are invented Hasok Chang (2004) calls thus the development of measurementation as "hunting for real value". Hunt for a constant feature in the laboratory world of nomological machines (Cartwright 1999) which scientists motivationally assume to exist but which about they cannot know. This is the limit of science expressed with quantities: there is no science without tehcnological interaction.

4.2 TECHNOSCIENTIFIC MODELLING IN GENERATIVE KNOWLEDGE CONSTRUCTION

The traditional views on modelling emphasize the role of models as representations and perceive them as ”virtual experimentation” or as a continuation of theorizing (see the section 2.1.3). In scientific practises the development of models and simulating in the virtual world often plays a central role in developing both theoretical ideas and the means to study these ideas experimentally. This kind of research breaks the traditional image of experimental sciences (Humphreys 2004). Computer models and simulations do not easily fit into one or the other of the traditional categories, not in that of theory nor in that of experiment. Instead, they behave like theoretical work in one respect and like experimentation in another (Dowling 1999; Godfrey-Smith 2006; Knuuttila 2005). Additionally, since the interaction between theoretical and empirical realities provided by modelling is inherently bound to our technological capacity, the need to develop and use computer models and simulations brings new kinds of creative components of knowledge construction into science. The modelling process makes the experimental machines an integral part of the knowledge generation-justification cycle, in which success in producing knowledge establishes not only new knowledge, but also the reliability of machines and computer codes.[41] From the technoscientific viewpoint, it can be argued that modelling amalgamates the experimental control and conceptual understanding of phenomena under study in a special way, providing an apparent kind of “understanding by control” in the virtual world, oriented toward practical skilfulness in design in both modelling and experimentation and the ability to predict on the basis of experience (Article I; cf. Lenhard 2006). The practitioners’ perspective that models and modelling are essential not only epistemologically but also methodologically emphasizes their role as tools of investigation even over their role as tools of description (cf. Cartwright 1999b; Morrison & Morgan 1999; Nersessian 1995). Such tools are quite autonomous because they function in a way that is partially independent of experimentation and in many cases they are constructed with a minimal reliance on high level theory (Morrison 1999). However, this does not mean that theory would play only a small role in model building and design.

In scientific practise, the value of models largely depends on how they can serve as somewhat autonomous, freely developing tools of creative thinking and for exploring ideas. To such a role of models as tools of investigation or vehicles of creative thought, the term “generative modelling” (Article II) is applied. This

41 At the concrete level, recent modelling typically means employing and often developing a kind of computer software, namely “coding”. Then the products of such modelling will include not only new scientific knowledge but also technological artefacts and knowledge, such as a functional computer code for a model, code for its virtual environment or a combination of such previously developed artefacts. Success in producing new knowledge also establishes the reliability of experimental machines and computer codes included in the process. To be able to develop such functional virtual systems or artefacts and show that they function as suggested, young scientists must also learn some technological means of construction and justification. (Article I).

shares many aspects with 'constructive modelling' and 'generic modelling' discussed by Nersessian (2008, 1995). In generative modelling, the 'running of a model' – either mentally in the form of simulative reasoning or more methodically by using computing algorithms and computers – unfolds the system's dynamical behaviour. The dynamic unfolding of the model in simulations is important because it plays a role in both developing the model and in understanding the processes behind various phenomena through modelling. However, although the purpose of such modelling is to understand phenomena, the models may not always be realistic representations of the systems or the processes and neither deduced directly from theories (an example is discussed in section 5). While modelling places both theoretical as well as empirical elements into models, it creatively bridges the conceptual reality and the real phenomena manipulated by experimentalists in laboratories. In recent science, this kind of generative modelling is thus often the missing link between experimentation and theorising, through which empirical adequacy of the models of the lowest levels of theories, is achieved. In conclusion, recent work in science studies into ways of thinking and of practising scientists' use of models support the ideas that models serve the exploration of new ideas in semi-autonomous ways. Such models mediate between experiments and theory. They are instrumentally reliable rather than 'true' (Article II). This kind of generative modelling is explained by empasizing its technoscientific nature in this section on a theoretical basis (see also Article II) and in section 5 from the empirical viewpoint.

4.2.1 Modelling as Fitting the Nomological Machines

What is reached in generative modelling can be explained with an ancient metaphor comparing nature to a machine. An experimental specimen or system is assumed to function as one of the world's machines with capacities to generate a "natural" change when sufficiently agitated by a mediating experimental technology (Cartwright 1999a). Thus, physical laws obtain upon the capacities of such systems. The idea of an experimental system as a nomological machine is apparent in the development of laboratory phenomena in the tradition of mimetic experimentation in the 18th and 19th centuries (section 4.1.2). It is illustrative also in explaining how the present modelling is fitted with experimentation, because the metaphor guides attention toward the functioning (instead of the structure). On a different basis, both material and virtual nomological machines embody a limited piece of the reality they are part of. A central role in the fitting is played by experimental and simulation runs, which means running the material and respective virtual nomological machines in order to compare those on the basis of the experience reached by running them. What is reached in such a fit is the partial **mimetic similarity** between the functioning of the phenomenon in the virtual and the phenomenon in the material world (for details, see Article II). This means that the processual evolution of systems in simulations should mimic the corresponding (though not exactly similar) systems in experiments, or, where experimentation is limited, what would have happened as predicted by more general theoretical models. The generative modelling plays an important role in the areas where experimentation is limited and the material nomological machine can only be partially realized.

Finally, models become validated by their ability to produce the intended effects: a new model is good if it produces the events observed in experiments (or may be predicted by more general theoretical models). Such simulative modelling serves to construct and validate **instrumentally reliable models** for the processes behind experimentally accessible phenomena (Articles II & III). These models embody the knowledge achieved by producing and developing simulation models. A large amount of technological knowledge is linked to such embodied knowledge. This technoscientific knowledge, in turn, becomes iteratively developed in the interaction of theoretical and material worlds. Furthermore, physical understanding is subsequently validated when provided successful in such modelling processes. It is the framework of the design process, which is developed in consequence. Success in modelling also increases the scientists' confidence in the means and techniques employed in designing, constructing and employing the model: the justification of methods and techniques constructed and employed in modelling lies in the pragmatic, scientific determination of whether they work or not.

As a consequence, the primary product of modelling is instrumentally reliable models for the processes behind experimentally accessible phenomena. In such a case, physical knowledge comes from understanding the functional role of ideas in the nomological machines fitted together. As a result, computer modelling not only constantly changes how humans do science but also how we perceive the physical world; the capacities of virtual, computer models give rise to the apparently regular behaviour of the "world" that we express with our physical laws.

4.2.2 Models as Two-sided Instruments for Investigation

In knowledge production, the simulations can be seen to be used as the numerical counterpart of the empirical instruments, compensating for the limits in accuracy in experimental control in the material world. As an **instrument of investigation**, generative modelling is related to the world of concepts and theories in parallel fashion to the way in which the measurement instruments relate to real systems; both are probes in their own worlds, about which they deliver information (Article II). When a model embodies both "know-that" and "know-how" knowledge, it has two dimensions: the computer models manage to simultaneously be epistemic objects and tools, and technological objects and tools.[42] As technological tools, what is valued is the closure of the models (while merging local and general knowledge), that is, the potential straightforward application of general knowledge developed in them. As epistemic tools they are flexible and open-ended: with regard to flexibility, playing in the virtual world provides them with a chance to construct and study systems with unrealistic characteristics, such as being extremely reduced (for details, see Article III). As for open-endedness, these models are able to behave unpredictably when pushed, which differentiates them from purely theoretical calculations. As a consequence, a models' epistemological value is based on its technological realization, which both limits and shapes it.

42 cf. Boon & Knuuttila (2009), Knorr Cetina (1997, 1999), Knuuttila & Voutilainen (2003), and Rheinberg (1997).

4.2.3 Fitting between Theoretical and Material Models

The design of a model takes place in the developing theoretical framework, namely models and simulation environments are constructed in respect with established theoretical models of higher levels and on the basis of the developing ideas at the lowest level. Moreover, these are developed in close interaction with the experimental results and processes. That is why the models have a possibility to **mediate** between high-level generic models (or theory) and experimentally accessible phenomena. When the models are adjusted to fit phenomena through the design process, where also laboratory phenomena are designed to fit the models, the experimentally accessible phenomena become fitted through models to the developing theoretical understanding. This is how the lowest levels of conceptual models (can) attain empirical reliability or adequacy. As a result the models and simulations behave in the same way as theoretical work in one respect and as experimentation in another, but are not directly derived from either, and thus are able to advance the development of both (cf. Dowling 1999; Morrison & Morgan 1999). Generative modelling thus functions as a developing link between the material and theoretical control over phenomena.

In sum, in the scientific practices generative or simulative modelling seems to play the following roles, which are not yet reflected in science education (Article III):

1. Generative modelling is a two-sided instrument of investigation.
2. Modelling aims to establish partial mimetic similarity between the processual evolution of simulations and corresponding (potential) laboratory phenomena, which are fitted to each other.
3. Modelling serves to design instrumentally reliable models, embodying the physical and technological knowledge achieved by developing simulation models.
4. Generative modelling mediates between theory and experimentally accessible phenomena.

Ultimately, these claims will be considered from the viewpoint of how those become revised by the empirical study among modellers working in the fields of materials physics and nanophysics. Because those fields are partly based on well-known theoretical grounds, we have all reasons to expect the traditional, clear theory-to-model relation and a preference to strive for realistic descriptions and attempts to establish similarity between a model and the modelled system. Nevertheless, as introduced in the following, the nanomodelling practitioners seem also to employ extra-theoretical elements and an instrumental rather than a realistic position. Instead of similarity with real systems, they emphasize practical values in reasoning and a certain type of mimetic similarity (though not in the sense of direct visual similarity) as a part of it. These viewpoints may differ substantially from the views these scientists have been taught in their earlier education.

5. THE PRACTITIONERS’ PICTURE OF KNOWLEDGE CONSTRUCTION THROUGH MODELLING

So far the ideas characterizing technoscience (Article I) and generative modelling (article II) has been introduced as theoretical, but in the form they are developed here they seem to arise quite naturally in discussions with the practising scientists and as an underpinning of actual scientific practises. Nanophysics, the activities of which are closely connected with the advancement of technology and where modelling and simulations are extensively used, is a natural place to test the ideas concerning technoscience. In research carried out at nanoscale, even the objects under study are artefacts and, further, nothing can be studied without advanced technology (for examples, see Article III; Hofer et al. 2003; Pitt 2004; Vvedensky 2004). Also the applications and products of nanoscience are quite technological, and interviewed scientists (informants) have to clearly refer to these “nano-, medi-, and bio-” applications (an apprentice = A)[43], when applying for funding or writing their publications. To be exact, the interviewees do “application-motivated basic research” in condensed matter physics, working mainly with nanostructures and nanoscale[44] processes. The relevance of this kind of research is apparent, because “materials and the ability to control their properties is the basis of technological development” (an expert = E).

In the context of interviewees’ computer modelling, physics is constructed through technological action which means creation of virtual systems and their manipulation for control in the virtual world, which then indeed provides conceptual and material control over the phenomenon studied (Article III). Every informant mentioned how computational and technological abilities define what can be studied, and how. In this way the technological, financial and other human needs constitutes boundaries within and between the research projects even before launching one and then guide the process from methods to products. As a consequence, creatively developed and employed modelling technology plays a central epistemological and cognitive role in their knowledge-building, to the extent that it influences scientists’ positions about what exist in the world and how it does it. The new theoretical ideas become more deeply explained by the nanomodellers’ practical viewpoints as introduced in the following.

43 Verbatim citations illustrate the common views presented in the interviews by contextualized examples or at a general level; those are employed in sections 5, 6 and 8 in order to animate the text.

44 For convenience, small scale is referred to here, although it is not only the length of scale but also quantum mechanical behaviour which defines and characterizes nanoscience.

5.1 ITERATIVE DESIGN OF MODELLING FOR UNDERSTANDING THROUGH CONTROL

The informants have been working with Molecular Dynamic (MD) simulations, thus running models in the virtual environment, describing the motion of particles in a deterministic way by integrating Newtonian equations.[45] Most of their modelling activity focuses on developing suitable and accurate (pair) potential models, describing the situations of interest. While the virtual environment is developed on the basis of classical mechanics, the coarse version of the pair potentials are based on quantum mechanical description of particle systems.[46] This is the theoretical framework or basis shared with all their MD modelling. Naturally, this is due to the phenomenon modelled, whereby also included in modelling design are other theoretical ideas and informed guesses.[47] The deductive power of the theories have severe practical limitations, however. In the process of deduction "one has to coarse grain after coarse graining", i.e. to reduce description of the phenomenon in terms of reduced degrees of freedom or with coarser spatial and temporal scales. This is reasoned by both technological limits – namely recent computational power available – and cognitive reasons: "if a model becomes too complex it is no longer intuitively clear" (A). In constructing the coarse versions of the models as calculable as possible, they employ templates, "simplified mathematical gizmos"(A) or models, which surface as the basis of model construction in a variety of fields of study (see Article II; cf. Humphreys 2004).

In practice, modelling is gaining understanding about phenomenon through "hands-on" construction and manipulation of the various models: different "simulations are quite down-to-earth, but at the same time [they] make it possible to study general phenomena"(E). When the objective of modelling is to understand the phenomenon at an empirical level and produce functional models for that, the modelling work concentrates on fitting together the coarse version of the model under development and the experimental results available; this is what the informants' contextualized descriptions focus on. On the other hand, the experimentalists need a model to plan the experimentation and to interpret the data gained therein: "Not simply to explain but also to understand"(E). This means that they can control processes in the nanoenvironment, even to the extent of being able to control

45 In the widely used MD simulation technique one generates the atomic trajectories of a system of N particles by numerical integration of Newton's equation of motion, for a specific interatomic potential model, with selected initial conditions and boundary conditions. In virtual reality, the atoms and molecules are allowed to interact for a certain period of time, while their motion is solved numerically. By such simulation runs, the modellers can study how the models function.

46 A pair potential model describes the potential energy of two interacting objects; the large systems are modelled by counting on basis of the models describing the interaction between the participating molecules. For details, see Article III; for a detailed example, see Salonen et al. (2001) and for a discussion about scales vs. different methods, see Vvedensky (2004).

47 For example, when one of the informants aims to model "cellulose and different ion-solvents as realistically as possible, in order to 'see' how the solvents break down the hydrogen bonds between glucose chains of cellulose and then to compare different solvents", he has to consider the previous theoretical understanding of organic chemistry (defining e.g. the nature of bonding between atoms and distribution of charge in molecules).

nanoconveyers and minimachines, when they have learned to use computers to do so. On the one hand, the models are judged by "tests of the model by experiment: to be precise, the predictions made by the model"(E). At best, "the simulation predicts something that will be found out in experimentation in the future"(E, A). As a result, not only are models adjusted to the phenomena, but the phenomena (re)created in the laboratory are in turn fitted to the models (see Article III). In consequence, such match-making is a two-way process: to theory connected computer models become fitted to the material models manipulated in experiments, and these material models are then designed and constructed in a way that fits with the computer models.

The model-building that aims for the fit between experimental and theoretical understanding is a cyclical process connecting scientific and technological, theoretical and empirical knowledge at different levels. Figure 4 sketches out the process as it appeared in the interviews with the modelling experts. The cycles in which modelling is thought to converge towards appropriate tools to investigate "the physical reality" is shown with bold arrows.

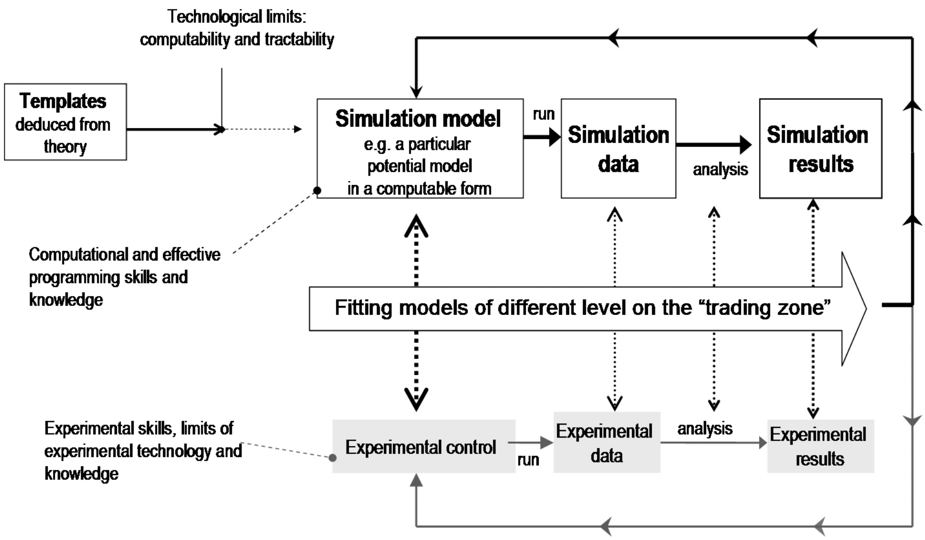

Figure 4: The modelling process as sketched with practitioners: modelling develops in interaction with the respective experimental process (cf. the technoscientific design cycle in Figure 3).

What exactly is compared in this fit, is the outcome of the simulations and experimental runs, where it is naturally considered also how the setups differ. Modellers emphasize that contrary to experimenters, they can follow what happens during the process in order to provide understanding. However, due to the limitations of computational power, the time and length of scales of the experimental and simulation runs do not converge. Thus, much interpretation comes between.[48] Furthermore, as is evident from the interviewees' descriptions, the models used in guiding the experimental design and interpretation of the results are often those which are under construction to fit with these same experimental results. At the same time modelling becomes developed with this objective of guiding in mind and it is validated by its ability to do it. The interviewees' modelling thus provides a concrete example also of the problem of "experimenters' regress" (Article I or Collins 1985; Nickles 1989; MacKenzie 1989) and how practitioners deal with the challenge. First of all, they aim to produce functional knowledge and the means to study it (instead of discovering human-independent "nature"), development of which is apparently provided by their constructive view. Referring to the origin of such constructive knowledge-building, an expert noted: "We should not forget that we are studying mental projections; we study mental pictures which are foundationally mental. It is what we see".

Especially when there are no experimental results available of the particular situation, the outcome of the simulation run is often compared with other available models or on deeper theories based on calculations.[49] Moreover, the informants mention that "everything available"(E) is used in fitting the models to explain experimentation, including much technological knowledge and even "plain hand-waving[50], in situations where we do not know what exactly is taking place"(E). In fact, they use as many sources of knowledge and means as are available (cf. Cartwright 1999b; Morrison 1999; Morrison & Morgan 1999; Winsberg 1999). Rather than being a problem, the diversity and complexity of the models' background is vital for fitting also between different models. In such design processes is developed functional models, methods, and also technoscientific understanding.

5.2 INSTRUMENTAL GOAL OF MATCH-MAKING

It is interesting to note that even in the described case of Molecular Dynamics simulations, which are often thought to be geared towards maximal realism, there is a strong sense of pragmatic instrumentalism. Informants' descriptions of the model-building process concentrate primarily on the technical and practical questions and descriptions of justifying the models concentrate on instrumental reliability and functionality. The objective is to construct a "model, which includes the essential

48 The role of interpretation models in scientific match-making is also taken into account in the theoretical studies (e.g., Hughes 1997; Suárez 1999).

49 When employing the different deeper theoretical calculations, either the accurateness of description or the number of atoms included is limited: quantum mechanical description defining the all interactions between particles is solvable in the case of hydrogen, but in order to extent the complexity approximations are needed. For example density functional theory (DFT), basing on idea of equilibrium distribution of electrons, which "already is quite scarce generalization, but even such a calculation technique is as a complex that it can applied only to a system with tens of atoms"(A).

50 The "hand-waving" ideas are naturally educated guesses, which they construct on the basis of their diverse experience and familiarity with the situation together with creativity.

[features of] processes and not much else"(E). It is enough that "in some cases the model is workable when estimating certain things. What makes it [a model] interesting is that we can take into account certain important aspects – or the simplicity"(E). "If it [the model] becomes too complicated, it is no longer intuitively clear"(A). Thus, the demands for practical tractability and feasibility of simulations override the striving for realism. The informants emphasized that instrumental attitude by saying, for example, that to some extent "a model doesn't care about the actual conditions or claims that it explains, since the only important property of a model is its functionality"(A).

The practical limitations and constraints posed by computational tractability and the computational techniques have also surfaced in other ways: "Owing to the digital nature of computers, the discretized template – which is the physical model fitted in the computer – is never the same as the original physical template which provided the starting point."(E) Such model can have "new characteristics, which were not included in the original physical model – of which the chaotic nature [of dynamics] is an example – and representations which were included in the original continuum model may have been missed"(E). Naturally, the state of technological ability limits substantially what can be modelled and how it can be modelled: a huge part of the modellers' work concentrates on balancing between technological limitations and scientific interests.

As a consequence, what is reached through modelling is the functionality and usability of the model and partial empirical reliability between the simulation model and material model, on the one hand, and with the essential parts of the models of theory and the simulation model, on the other hand. The interviewees do not refer to structural similarity, but instead to the idea that the rules underling the processes in simulations (its features in focus at the moment) are tailored to be similar with the regularities assumed to underlie the experimental systems. Thus, on the basis of the interviews – which are supported by recent theoretical studies (e.g., Humphreys 2004; Morrison & Morgan 1999; Rheinberger 1997) – representation is only one role of models and indeed is more limited role than the recently favoured views of models and modelling in science imply (see Article II). By extending their views, namely adopting an instrumental attitude towards both models and the knowledge included in it and developed thereby, scientists achieve more.

5.3 MODELLING AS AN INDEPENDENT INSTRUMENT OF KNOWLEDGE CONSTRUCTION

In addition to material control, the objective of modelling is to produce conceptual control over the phenomenon under study, which is enabled by the fact that modelling takes place in the scientific, theoretical framework (see 5.1). The mediating models carry a substantial amount of well-articulated theoretical knowledge but those have not, in any case, been deduced and derived from theory (see 5.2); otherwise nothing new would come out of modelling. The interviewees described several examples of how playing in the virtual world also provides them opportunity to construct and study systems with properties which may not be real within the given theory. Sometimes such systems are extremely reduced or idealised, and when needed, even contradict some theoretical principles. Because models are not deduced from experimental results either, those can guide action in the experimental world, from planning the experimental setup to the interpretation of the results (Article III). Such partly independent tools of thinking in the conceptual or virtual world allow one to explore theoretical possibilities in interaction with the experimental world.

The capability of models to mediate between theoretical and experimental control by developing both, rests on their instrumental reliability and relative independence. The modellers highlighted the quite autonomous role of models and modelling also at the general level: "A model lives its own life."(E) Such a model is a central epistemic object in nanoscientific knowledge construction: "It is a model which explains a particular physical phenomenon. And then everyone follows that model. The model is probably fine and correct, and sometimes it is not. But experimenters start thinking in terms proposed by this 'theory'."(E) When a model creatively merges theoretical understanding with experimental knowing in a closed, virtual process, it is an effective instrument for investigation and communication. Finally, what is achieved in a knowledge construction process embodied in the modelling, is functional and empirically (partially) reliable models and advancement in both experimental control and its scientific understanding. Successful modelling also increases rest on the reliability of the method, models and templates employed.

In consequence, technoscientific views (Article I) – and the ideas of generative modelling (Article II) – have become supported and contextualized through the views of practitioners of nanoscience. Since these findings are from the rather conventional field of materials science, similar attitudes and stances may also be typical of many other branches of the physical sciences. After all, using models as tools for thinking rather than as tools for realistic representations, or striving for instrumental and practical values instead of realism, may in practice prove far more common than that envisioned by philosophers holding to realism, and especially to representational realism. Then also the view on the expertise developed in such research practises provides scientists with new possibilities; the next section explores the expertise developed in such modelling.

6. NANOSCIENTISTS' EXPERTISE

Since the interaction between theoretical and empirical realities provided by modelling is inherently bound to our technological capacity, it is no wonder that many informants mentioned that enculturation into the modelling means hands-on "practising and practising" on modelling and simulations in order to master the multidimensional field. At the concrete level, recent modelling typically means employing and often developing a kind of computer software, namely "coding". Then the products of such modelling will include not only new scientific knowledge but also technological artefacts and knowledge, such as a functional computer code for a model, code for its virtual environment or a combination of such previously developed artefacts. In this construction needed basic theoretical understanding – physics, chemistry and mathematics – and the basic programming knowledge can be reached by studying in course-based settings. To gain effective technological skills, namely programming skills, a lot of practising is needed. This is not enough, however.

Modellers also need to acquire special technoscientific insight. When speaking about creation and decision making at different stages of a modelling process in the particular research situations they gave as examples, every interviewer frequently referred to his or her "special insight into modelling", "a sixth sense" or material physic specialists' "physical intuition". It was said to guide the evaluation and to convince colleagues of the functionality of a new idea, model or simulation being developed. The epistemological and methodological ideas underlining this "sixth sense" are not discussed explicitly in education, but in time, the successful apprentices learn to see the particular problems they are dealing with through the eyes of the experts; that is, they learn to see in the particular situations what to simulate and model as well as how to simulate and model. This kind of understanding of the basis of knowledge-building in the virtual world lays the groundwork for the expertise that apprentices need to acquire – and it is developed by acting in the technoscientific practises embedded in the community.

Expertise research has previously concentrated largely on individual cognitive performance. However, interactive expertise (Collins & Evans 2007) seems to play an important role in success: young scientists need to develop an ability to communicate and co-operate in developing their ideas, activities and interpretations. In studies on expertise in software engineering, a field which has much in common with the domain of scientific modellers', it has been noted that high-performing individuals spend more time and show better competencies in communication and cooperation than moderate performers (cf. Sonnentag 1995; Sonnentag et al. 2006). The interviewees of this study, perceive especially the ability to build and maintain the co-operation with experimenters as being vital for the field of modelling: only through this interaction can they build the connections between virtual and material models, and thereby increase understanding of the phenomena under study.

Co-operation also provides fruitful places to reflect on the possibilities and limits of one's own field of study.

Moreover, in such an interdisciplinary and evidently technoscientific field as nanomodelling, the expertise guiding application of the acquired abilities into other fields of research and development is of central importance for both individual success and scientific and technological progress. After writing a dissertation the apprentice should be able to "sell" and apply her/his expertise for employment in other contexts. The technological skills and understanding needed and reached through modelling are evidently transferable and the virtual insight applied in an increasing number of fields. Indeed, specific aspects of experience, such as its breadth and variety, are related to expert performance (cf. Sonnentag et al. 2006) – the apprentices with a more varied experience were more quick to reflect on their work in the interviews and they seemed to work more independently than the apprentices having less varied expertise. But the practise, where apprentices concentrate on one limited, research topic, do not support the development of such an ability to apply one's expertise in new fields. In the following, the modellers' expertise is introduced as developed through practising. The discussion is divided into three parts: developing the expertise needed for contributing to the model building; the expertise needed for build the connections to experimentation; and the expertise needed to apply one's own expertise into new contexts (for details and examples, see Articles III & IV)

6.1 TRYING TO ACHIEVE THE "SPECIAL INSIGHT INTO MODELLING"

The epistemology of the modelling practices (discussed in section 5) develops in the dynamic scientific process respecting both what is valued by the scientific community and individuals' attempt to understand it. Apprentices are supposed to catch that **"special insight into modelling"** indirectly. In the beginning, an apprentice uses the given method(s) and models as black-boxes, when solving the tasks given by expert(s); the primary task of the apprentice is to find out how the black-box functions. Namely, (s)he gains user knowledge of the investigation tools used and developed in the field. Unlike a typical educational tool, the function of the models and methods, which apprentices use, is not thoroughly known in advance (even by experts), because the apprentices are participating in authentic research practises. Then the apprentice aims to adapt the given tools in order to answer the given questions, developing himself or herself by trial-and-error and in interaction with peers and experts. In this way (s)he learns to address the practical arguments underlying modelling. Through practising, successful apprentices finally gain tacit understanding about the basis and limits of the methods in both technological and scientific terms. On the basis of this understanding, in time the apprentices are supposed to learn to primarily develop the models and codes – as the most experienced apprentices were doing – and later on may also develop methods.

An important question in understanding the modelling process and its products is the relation between modelling and “reality”: namely, what can be said to be achieved by modelling and on what basis. At the beginning of enculturation, the interviewed apprentices seem to have a tendency towards overarching realism. Quite soon they realise that there are no simple rules for assessing a model and that, contrary to their previous education, modelling is not a simple deductive process — from theory down to simulation data. Instead, they learn to mix realistic arguments of construction and justification with pragmatic ones, which means employing both scientific and technological knowledge and logic. When advancing, the successful apprentices adopt the experts’ flexible, instrumental view: the longer they have practiced modelling, the more the apprentices’ views on modelling and its relation to reality seems to become increasingly technoscientific, instrumental and moderately realistic (see Article III). Differing experience – working in both experimentation and modelling, for example – together with interdisciplinary discussions seem to accelerate such a development (see III). In sum, the primary objective of practising in the apprentice-master system is that young modellers learn to develop models on the basis of quite an instrumental and moderately realistic epistemology. Furthermore, the apprentices should learn to develop modelling in such an iterative way that finally the models are based on both theory and experimental values; some are naturally closer to theoretical calculations and others closer to an experimental process.

6.2 TRADING ZONE EXPERTISE FOR CONNECTING THE REAL AND VIRTUAL WORLDS

The beginning apprentices perceive simpler interaction between experimentation and modelling than the experts: while experts perceive the interaction to take place on every level of the process which then iteratively defines and figures both activities, the beginning apprentices see the interaction as an exchange of the established results (see Figure 5). The more advanced level an apprentice achieves, the more merged (s)he considers the mental and material control over phenomena.

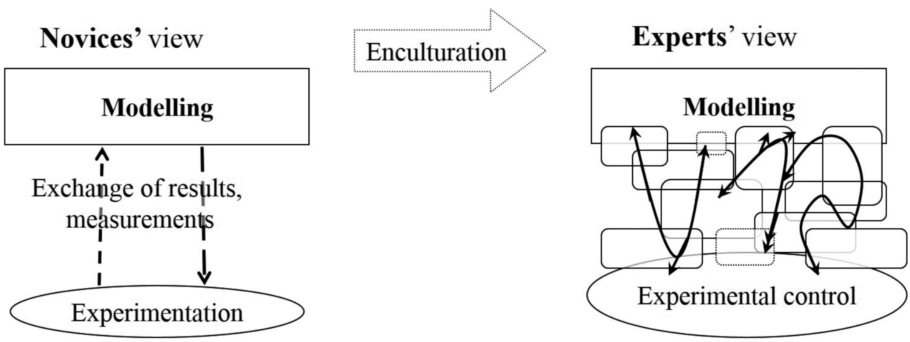

Figure 5: During their enculturation, apprentices should understand and then also learn to tailor the various, overlapping modes and means of trading.

Because the generative modelling functions as a developing link between the material and theoretical control over phenomena, the apprentice modellers need to develop an ability to maintain the interaction between experimenters and modellers, and also with the experts dealing with the theory providing the framework of their modelling. The interaction between the communities with different methodological approaches, is a kind of *trading* (Galison 1997) of ideas, methodological abilities, resources, models, explanations and data – and thus the ability to facilitate the interaction on the trading zone is here called **trading zone expertise**. It is vital for modellers' success, because models and modelling become reasoned through this comparison. Also their expertise as such seems to be a kind of merchandise: for example, visiting another group, was a prerequisite to providing the coarse version of the model an interviewed apprentice and expert needed. Such working visits are effective in terms of transfer of tacit knowledge and skills nurtured in a group.

The knowledge-building communities do not only have different methodological approaches, but also different practical objectives, different methodological and thus also epistemological views along with terminology and cultures of communication. In addition to the understanding of the basis, limits and potential of their own approach, intermediate modellers need some understanding of the basis for the experimental and theoretical approaches. The diverse experience employed in developing such understanding, the reflective and socially curious apprentices seem to organize also by themselves. The amount of natural interaction with the experimenters vary due to the level of activity and research projects (s)he is participating in. To be able to build the connections to theory and experimentation through interaction, young nanomodellers need to learn and also develop inter-cultural modes of communication (cf. Collins et al. 2007; Ribeiro 2007; Wenger & Snyder 2000). Because nanomodelling is a young, developing field, there is no established basis for terminology or other means of communicating innovative ideas[51] and thus young modellers should learn to employ and develop the context-specific communication between the different subcultures. It is primarily the intermediary modellers' role to develop the modes of communication as well as the epistemic objects embodying the co-operative working.

The models provided by nanomodellers facilitate the interaction in a special way, as an expert explained in general terms: "What is important in the dialogue between experimentalists and theorists, is a very simple, maybe idealized model, a simple mental picture.... It is not true in reality, but it somehow gives you some sort of mental picture and makes understanding the complicated phenomena easier, again in terms of everyday experience"(E). The models are kinds of boundary objects (cf. Galison 1997; Wenger & Snyder 2000): "It is a model, which explains a particular

51 Notice the relatively small size and young age of the Finnish group (section 3.2). The nature of trading zones changes when the institutes of cooperation are established, for example when groups of different practitioners are in permanent cooperation and even work in the same building (Collins et al. 2007). This development can regularize the nature of the language and other means of communication used. To reach such a state of development in a new field, and at the international level, generations of new researchers may need to be educated.

physical phenomenon... experimentalists start thinking in terms proposed by this 'theory'"(E). Naturally, other modes of communication are also needed. According to an expert, "the reduction of the data and visualization is important"(E) in the communication on the trading zone: the interviewers frequently mentioned how visualization (including pictures, graphical plots, scaling plots, etc.) is used (as an epistemic tool) in tailoring the procedural similarity between the virtual and experimental processes. Visualizations guide communication for shared understanding; "you cannot understand the phenomena, or the structure on the basis of pure numbers"(E).[52] Then, the visualization enables the co-operators to see whether "the simulation produces it correctly" (N, E), as observed in the experiments, which are presented in the same format.

Trading also provides creativity: interviewees mentioned examples of how discussion with or publications by scientists coming from other fields have given birth to innovative ideas. A young modeller, who seemed to be exceptionally active in seeking such discussions, stated: "You speak with another researcher and then suddenly, a new idea appears in your discussion"(A). This kind of interaction also develops the ability to apply expertise in new fields, as 'the adaptive expertise' or 'the referred expertise'.

6.3 EXPERTISE GUIDING APPLICATION OF ONE'S EXPERTISE

One's ability to transfer expertise to other fields is especially important in the scientific fields related to rapidly developing technology, such as computer software and hardware, where new tools and methodologies continue to emerge and where existing knowledge and methods can quickly become obsolete. Few of the interviewed experts' careers have concentrated on MD simulations in physics until now and few – if any – of the apprentices will work only by this method in the field of nanophysics or even in material sciences in their future career. Instead, in such rapidly developing fields we see successful attempts to bridge different disciplines by experts acting as "brokers" in the transfer of methods and perspectives to other fields or by producing boundary objects transferring know-how (cf. Galison 1997; Knuuttila & Loettgers 2013; Wenger & Snyder 2000). Ability to apply expertise in new fields is the key to both individual success – and scientific and technological progress.

Developing understanding of the possible transferability of a method seems to occur in a young scientist, when (s)he engages in diverse working experiences, or when (s)he is included in the developmental work. Technoscientific abilities, such as modellers' ability to develop computationally undemanding and effective models and to tailor the modelling process within the given technological limits, are apparently transferable. Even the method the interviewers employ most of the time, MD simulation, is a new and flexible method. For the general physical basis,

52 "Of course, plenty of numerical values are always produced in experimentation and one can claim that a number stands for something, but it is not true. Firstly, comes the interpretation of the observation"(E).

it is applicable to different problems: "The MD is a generic method that can be employed even in astronomy, in which the scales used are entirely different [from the atomic scale]"(E) (for an example, see Salmela & Nordlund 2008). Furthermore, the modellers described how the mathematical models and computing algorithms, by which simulations are implemented into computers, remains independent of the specific scientific context of their development: this increases substantially the transferability of their methods. They use these templates in simulating numerous different materials that aid in the transfer of expertise from one context to another. Such expertise includes, for example, methodological knowledge, skills and tricks. As one expert modeller remarked: "one of the strengths of our group is that what we have learned about [modelling] metals can be used directly in explaining a phenomenon connected to carbon nanotubes and vice versa" (for an example, see Järvi et al. 2007). Those can be used to study phenomenon even outside of physics.

At best, an apprentice merely reaches the ability to extend the known possibilities of the methods. According to the interviewed experts, for many nanomodellers – like other young scientists working in new interdisciplinary fields – it is not enough to be able to apply the methods only in the scientific contexts: "The companies are interested in whether people are able to model... But it is not really modelling of physical phenomena; it is modelling of a particular process"(E). As a successful example of the development of referred expertise, an expert reported that a former apprentice now simulates situations in biophysics; some others simulate irradiation on tissue as medical physicists, and yet another one has simulated the development of stock quotations. In those activities they need the flexible ability to "deal with a huge amount of data [trying] to obtain some relevant knowledge from it".

In conclusion, in order to succeed after one's doctoral education, a young scientist should gain a wide view of the basis of the models, methods and applicability of them. Such expertise development seems to be supported by diverse experience, interdisciplinary working and its reflection, which could be supported and encouraged in groups (see section 8.1). Since scientific research is becoming increasingly interdisciplinary and modelling plays a role in an increasing number of fields of study, the three aspects of expertise discussed above play a role in scientists' success in increasingly many fields – and finally in scientific and technological progress.

7. DISCUSSION

This study scrutinized knowledge-building in physics for educational purposes, paying special attention to the role of technology. The multifaceted research problems were approached by both theoretical and empirical methods. The answer to the first research question involved developing a functional view to scientific knowledge construction, which is recognizable also by practising scientists (Articles I and II and the section 4). The answer to the second research question addressed the test and deepening of the developed theoretical views in the context of nanomodeling practices, in close co-operation with researchers working in the field (Articles III and II and the section 5). The answer to the third research question went a bit further, by considering the expertise that young scientists are acquiring by working in apprentice-master settings in an evidently technoscientific field of study, nanomodelling (Article IV and section 6). The results were developed here in the spirit of moderate constructionism or pragmatism (Bodner 1986): by working in co-operation with the practitioners, those ideas became valued, which seemed to be meaningful from the viewpoint of scientific practises and learning those practises. After summarizing the results, this section discusses the methodological questions related to the authenticity of the picture drawn of modellers' views.

7.1 SUMMARIZING TECHNOSCIENTIFIC KNOWLEDGE CONSTRUCTION

As discussed in this dissertation, the technological nature of science shapes the scientific process together with its products. The ideas condensed in the technoscientific view (Article I) and generative modelling (Article II) arise quite naturally in the interviews with practising modellers and then guide understanding of nanomodelling practices. Physics and technology are so intimately mutually interdependent that technology not only plays a central methodological but also an epistemological, cognitive and even ontological role in physical knowledge construction. The experimental knowing comes from the material and conceptual success in creating, manipulating and controlling laboratory phenomena.

At the heart of phy d cognitive control over phenomenon. It thus necessarily addresses both scientific and technological understanding, thereby developing both. Such technoscientific design is often embodied in generative modelling. As a result, generative modelling functions as a developing link between the material world produced and manipulated in experimentation and the abstract world of theoretical structures. Its ability to contribute to the development of both is based on the relative independence: models are neither mere solutions to our theoretical problems nor deduced from experimental results, and thus able to intervene in theory and finally guide action in the experimental world. Modellers address both experimental and theoretical means of justification together with quite technological means. Also in the interviews the reasoning for a model concentrate largely on practical questions dealing with the functionality of a model and an effective usage of available computer power.

The interviewed nanomodellers employ and develop modelling as a creative, partly independent tool of investigation, having both epistemic and technological sides. Thus the practitioners perceive the question of how models connect abstract and material reality, not as an ontological one (a question about what really exists in the world) – and often do not discuss it even as an epistemological question – but primarily they see it as a methodological question, a question about making a match: how is the empirical adequacy of these models of the lower levels constructed and justified. And in this process, the functionality of models, the ability to produce the intended outcomes, is of primary importance. At the core of nanomodellers' expertise thus seems to be a shared, instrumental view guiding their modelling, the products of which are both functional models and new scientific understanding. In order to maintain the models' role of mediation between theory and experimentation, nanomodellers need a strong 'trading zone' expertise. Indeed, the flexibility of the methods and the experience gained in mediation provides them with a variety of opportunities for application of their expertise in other contexts as referred expertise.

Technoscientific features seem to appear in all experimental science; for example, chemistry, where most explanatory models deal with a scale not attainable by human eyes, is evidently even more technoscientific field of study than physics. Indeed, models and simulations play important roles in a diverse field of sciences such as meteorology, neuroscience, cognition sciences, sociology, economics, and archaeology and but also outside of science: in social, economic and environmental prediction and decision-making. Thus, we need this understanding and means to support the development of expertise nurtured in knowledge generative modelling.

7.2 ESTIMATING THE AUTHENTICITY, APPROPRIATENESS AND TRUTHFULNESS OF THE EMPIRICAL STUDY

The traditional criteria for reliability and validity do not apply to the empirical part of the dissertation, because it is essentially a case study (e.g., Bassey 1999). Nevertheless, the principle of validity applies if it is understood broadly as the criteria of reasonability and appropriateness of the naturalistic approach as it is adapted to the cognitive-epistemological phenomenon. Respectively, reliability is here understood as "trustworthiness" (Lincoln & Cuba 1985; Patton 2002), considering credibility and conformability as criteria (cf. Lincoln & Cuba 1985; Marshall & Rossman 2011). At the concrete level, this means considering how the questionnaire and focused interviews supported informants' reflection of their practises and on the basis of which, how motivated the informants were to reflect and communicate honestly,[53] how successfully the case has been summarized and communicated, for example, and, with regard to the generalizability, how the sample represents the ideas nurtured among scientists doing similar research.

The informants were highly motivated in terms of co-operating and being truthful, because they also wanted to learn, support the learning in the group and to participate in the improvement of science education. After being interviewed, some of the informants spontaneously thanked the interviewer in supporting them to reflect: when carefully pondering their responses to the questionnaire and in the interview, they learned new things about the basis of their action and decision making. Additionally, when a couple of the interviewees – and their colleagues employing computer modelling as a research method in other fields – were later asked to participate in a similar study (see section 8.1), they were willing to participate again. Thus, we have all reasons to assume that they were honest in reflecting and communicating their views.

An essential point in securing authenticity and truthfulness is the contextualization of the general questions in a form meaningful to the informants, in the practises of the field and in the on-going research projects of the informants. This is comparable with the philosophers', sociologists' and historians' of science usage of the authentic documents in their research, where the detailed questions of the events related to the issue under discussion are asked in order to increase the informant's accuracy (cf. Bernard et al. 1984). But the contextualized interview takes the authenticity issue even further, since it allows the informant himself/herself to analyse his/her action and thinking from the viewpoints (s)he may have not considered before: contextualized interviewing is a kind of supported reflection, supported on the basis of the interdisciplinary groundwork (cf. Collins & Sanders 2007). The questionnaire used as a basis of the reflection were published (Article III) in order to increase the transparency of the process. The detailed descriptions of the sample (informants) guide assessing the applicability.

In phenomenography, the researcher is realized as one of the interpreters, co-constituting the reality under study, even the interviewer aims to reveal what is within the minds of the interviewees, as uncoloured and unaffected by the interviewer as possible. For example, at the level of analysis, the researcher contacted the informants in order to ask them to further explain the responses. It was also noted that the same viewpoints emerged repeatedly in the responses of the successful nanomodellers (reliability). At the end, each informant checked the analysis of the responses including the figures (validity, see Lincoln & Cuba 1985; Miles & Huberman 1994). The results have been communicated by employing verbatim citations and also examples, in order to let the readers to better capture the modellers' ideas. Finally, the results have been shown to be in line with at least with different theoretical

53 Here the interview study meets the problem widely known in anthropology: "if they (informants) tell lies, we tell lies" (see Metcalf 2002). However, what for they would want to tell lies when the objective is an educational one (to increase their own methodological self-understanding and to develop education)?

frameworks in the field of philosophy and education (repeatability, generalization): philosophy of technology and modelling in science (Article II; Morgan 2012), for science education applied philosophy of knowledge-building in physics and chemistry (Bernhard 2013; Kurki-Suonio 2011; Ribeiro and Pereisa 2013), modelling in science (Article II) and interaction between science and technology (Santilli 2012), studies about the nature of science and technology for science education (Hadjilouca et al. 2011; Laherto 2010; Nagl et al. 2012; Tala 2009b, 2013b; Tala & Vesterinen 2015; Vázquez–Alonso & García–Carmona 2014; Vesterinen et al. 2013), teaching science and technology for STL (Bungum 2014; Komazek, G. & Vuksan-Delic 2014; Elliot & Ashgar 2014; Levinson 2010), and theories of expertise development (Gerontas 2014; Tala 2013a).[54]

54 Until now, at least these studies referring to the Articles included in the dissertation, show how this study fit in current scientific discussion, science policy and science and technology teaching practices worldwide.

8. IMPLICATIONS

The primary implications of the study are in the field of higher education, and especially in the education of new researchers. As the informants of the empirical study frequently repeated, a central role in developing expertise in scientific knowledge construction is naturally played by practising in the authentic settings. They were highly interested in enhancing learning in such settings, primarily by studying their expertise embodied and nurtured in the research practises. As mentioned above, afterwards interviewees explained that they had learned something new in the interviews, while reflecting on the basis of their own action and thinking. This outcome encourages organising more such "education" (and accompanied research) about expertise embodied in research practises and the planning of PhD projects as considering these objectives (section 8.2). This study hopefully also encourages more interdisciplinary co-operation in order to support both practising scientists' methodological self-understanding and philosophers' understanding about scientific practices.

Another practical implication of this dissertation is that of encouraging science education at all levels to reflect on the practising scientists' viewpoints concerning the nature of contemporary scientific knowledge construction. The articulated viewpoints on scientific knowledge construction guide tailoring the contents and practises of science education at different levels as more authentic (section 8.2). Because teachers' views about the subject under study strongly shape the manner in which processes and products of science are discussed and studied, the secondary place to consider the new ideas is in teacher education. Also science education can be seen as more a matter of socialization into tacit ways of thinking and as developing skills than transferring explicit information.

8.1 IMPLICATIONS FOR EDUCATION OF SCIENTISTS

The development of expertise can be supported in apprentice scientists by providing them with explicit knowledge about the tacit components of expertise and tools for reflecting on the expertise they are acquiring. These tools provide the cognitive means to analyse the activity in which they are engaged, the basis and limits of the application of the approach used and developed there in, and, indeed, the basis and possibilities of the approaches employed by the (possible) co-operators. The reflective ability develops through practising it, by reflecting on practices wherein one is engaged. The naturalistic approach to scientific practises provides a basis for developing material and a series of questions for supporting reflection, of which the questionnaire developed for this study, is an example. The respective questions for experimenters, for example, can be constructed by focusing on the employed experimental skills, instruments and machines, their functionality in the intended tasks and relation to theory, modelling and the world outside of laboratories. Such patterns of questions constructed for contextualized interviewing, are valuable in the supervision of PhD research and education.

Reflection could also be taught by a course supporting expertise development. An expert suggested:

> *"We should have a course on the theory of scientific modelling. It should not teach modelling techniques, but should concentrate on questions (at the meta-level) like the ones you have just asked me (in this questionnaire and interview)... such a course could explain the theory of modelling, what kind of model is a good one and what kind of model is a bad one... It is not a technical question, but instead one that must extend the viewpoint beyond technical aspects."*

Such a course on a "meta-theory of modelling"(E) should discuss the basis of different modelling methods and, for the central role of trading-zone expertise in modelling, the course should be extended to the other methodological means, at least in discussing their relations to modelling. In order to acquire a wide perspective on their expertise, the apprentice researchers need interdisciplinary contexts for discussing and sharing diverse experiences (cf. Wenger & Snyder 2000). By practising reflective skills (cf. Kremer-Hayon 1988; Kompf & Bond 1995) in interdisciplinary contexts, namely by discussing the basis and possibilities of different methods with experts or apprentices coming from other fields, one learns to develop shared modes of communication and co-operation. Moreover, reflection on interdisciplinary context increases understanding of the applicability of the expertise one has, developing the referred expertise. In conclusion, teaching that aims to support the expertise-development of young scientists working in research groups, is natural to organize in interdisciplinary co-operation between, for example, (1) the practising scientists employing different methods in their research practices and willing to reflect their knowledge-building, (2) the researchers analysing the nature of scientific knowledge (e.g. philosophers) and (3) researchers informed by educational perspectives. In this way, the central analytical points are discussed as being closely connected to the scientific contexts, the conceptual and methodological practises of science.[55]

On courses aiming to develop young scientists' reflective abilities (Kompf 1995) and thereby an explicitly reflective and communicative culture in research groups, it is natural to employ discursive methods which encourage peer–peer interaction. Such a course could start, for example, by general introduction about expertise in scientific knowledge construction, basing on naturalistic analysis of scientific practices (see sections 3, 5 and 6, cf. Grüne-Yanoff 2014). The introduction could be followed, in turn, by a series of scientists' reflectively oriented lectures of their field of study and tutorials guided by a philosopher, educator and a practising scientist,

55 By applying the famous citation attributed to Richard Feynman, it can be said that un-contextualized philosophy of science is about as useful to scientists as ornithology is to birds. Philosophy benefits practising scientists only when it is applied in improving their acting and thinking.

where both the lectures and philosophical and scientific texts would be discussed. The final course work could be, for example, a reflective essay about the expertise nurtured in the group where the apprentice is working in (developed on the basis of a pattern of reflective questions and feedback). At best, such learning experience leads to ongoing reflection and the active participation in interdisciplinary discussions and development of ideas in one's future career: in such a light, learning is a continuous process grounded in experience (cf. Kolb 1984).

Education aiming to support the development of young scientists' reflective abilities and thereby their expertise, can also produce more empirical case studies like this. Such case studies from different fields of research are needed to further understand the scientists' knowledge-building expertise in order to support learning it and, thereby, promoting scientific and technological progress. In further studies, focus could be moved toward the development of shared understanding in research communities (section 8.3), in order to understand more deeply also the process wherein sociology becomes intertwined with epistemology.

8.2 IMPLICATIONS FOR SCIENCE EDUCATION AT LOWER LEVELS

In all science education, scientifically sound and authentic content is a natural starting point and the learning process itself at its best constitutes a dimension of the progress, which runs parallel to the progress in science itself (e.g., Fensham et al. 1995; Millar & Driver 1987; Nola 1998). In order to complete the picture provided about science, education reforms have worldwide included the ubiquitous goals of helping students develop informed, explicit conceptions about (the) nature of science (NOS) and its relations to society. This is reasoned by the need to educate citizens who understand and may participate in the public discussion about recent science and technology (STL) (e.g., Allchin 2013; Hodson 2008; Matthews 1998; Rudolph 2005), which is still under development. This dissertation study can be applied in improving science education toward this aim (see Articles I&II; Tala 2009b, 2013b; Tala & Vesterinen 2015). Articles I & II highlighted those features of scientific knowledge construction that should be considered in designing present science education.

In educational documents, the construct (the) "nature of science" is frequently defined and discussed at quite an abstract level. However, the nature of science can be understood and validated only when it is contextualized[56] in examples of scientific research and analysis of it.[57] In educational practises the nature of science is studied mostly by way of historical stories of science (e.g., Clough 2011; Paraskevopoulou

56 For example, Allchin (2011), Clough & Olson (2008), (Elby & Hammer 2001), Ford (2008), Lederman et al. (2002), Osborne et al. (2003), Sandoval (2005), and Schwartz et al. (2004).

57 Such a contextualization naturally encourages consideration of what is reached by the consensus lists of the statements of the nature of science (Tala & Vesterinen 2015).

& Koliopoulos 2011). This study encourages revising understanding promoted in education about NOS also in the contexts of contemporary science, by learning from practising scientists. Such an approach reflecting contemporary science provides the goal of science and technological literacy (STL) from the viewpoint of applicability and appropriateness.[58]

One obvious way to address the new views developed in this thesis in education is to use examples drawn from the analysed scientific practises in explicit explanation of NOS (Sandoval 2005), like narratives (Article I; Tala 2009b). Such explaining about the nature of science is always balancing between authenticity and simplicity[59]. In educational stories, concrete examples have to be included: exemplary cases of modelling projects, simulations and modelling activity and also people or groups and their relations and institutions are to be engaged. It is important to realize, for example, that scientific work is not such a straightforward process as historical re-written stories indicate, neither it is a miracle, but instead it includes much monotonous everyday duties, such as repairing real or virtual systems under study, preparing conference presentations, writing and re-writing, and become guided by personal motivation and financial factors. Living scientists are impressive examples of that. Moreover, nanoscience provides a good context within which to discuss the interaction between the technoscientific enterprises and society or every-day life. In the field of science education, also some understanding about nanoscience and nanotechnology and its relation to society has been noted as a relevant up-to-date example of scientific literacy (e.g., Gardnera et al. 2010; Laherto 2010; Shamos 1995; Zenner & Crone 2008). Students together with teachers may interview scientists by themselves by employing a simplified version of the questionnaire developed in this study.

Teachers' views guide discussion about experimentation and modelling in education together with the employment of practical activities. Modelling in contemporary science is an especially challenging theme in the current situation where implementation of the traditional theory-derived and more straightforward modelling approaches used in educational contexts is still relatively new. We thus employed a contextualized interview method with scientists in the teacher education course "Models and visualization" held in the Department of Chemistry in the autumn of 2013, where the objective was to support teacher students in developing an authentic picture of the nature of scientific modelling and provide them with a means of teaching it. The teacher students interviewed different modellers in physics and chemistry by employing a simplified version of the questionnaire developed in this dissertation study (see Article II). They also analysed their recorded interviews guided by questions that encouraged making generalizations and thereafter wrote

58 See Tala (2009b), Tala & Vesterinen (2015); cf. Allchin (2011), Alters (1997), and Laherto (2010). Also the wider social and institutional features are worth for considering, for example, when discussing with the living scientists (Erduran & Dagher 2014; Tala & Vesterinen 2015).

59 cf. Allchin (2011), Forato et al. (2012), Höttecke & Silva (2011), Metz et al. (2007), and Monk & Osborne (1997).

essays on this basis. The results indicate that the method also functions well as a studying method. In their essays, the teacher students refer to clear technoscientific and generative features of modelling (see Tala & Vesterinen 2015). The practising modellers working in different fields also clearly referred to such generative and technoscientific features in the interviews.[60] Specifically, many students mentioned the value of a deep discussion with a practitioner in the context of a particular case, that is, in understanding the nature of scientific modelling. Indeed, in the self-evaluation, one student, for example, mentioned that until the interview task, she had "never realized the significance of modelling as a tool for investigation". Another concluded: "I feel that it is important for me, as a teacher, to have such a perspective [on models and modelling]". Thus, the primary results indicate that such a study approach would also encourage teachers to value NOS as an instructional aim. The usage of the contextualized interview as a studying method is worth further study. In order to make NOS teaching effective , how school science activities and what is told about science reflect on contemporary scientists' viewpoints on science and the nature of science also has to be discussed (in both research and teacher education).

The best learning results are reached when recent understanding about the nature of science is both highlighted by explicit examples of nature of science and considered in designing educational solutions and discussion.[61] In the previous studies it has been noted that the epistemological authenticity of the educational practises is poor (e.g.,Abd-El-Khalick 2013; Chinn & Malhotra 2002; deVries 1997; Article I). Since the experimental work and associated skills of handling the experimental apparatus and measuring instruments has long been considered as an integral part of learning the sciences (Hodson 1986) and the model based view (MBV) is included in many curricula, the recent framework provide a good basis upon which to develop education in such a way that it promotes the cognitive, creative and constructive roles of technology and modelling in scientific knowledge construction (see Articles II & III).

The new views of technoscience and generative modelling well support constructively oriented teaching: the technological design process of any methodological means, interweaves the knowledge of different kinds and associated skills and abilities, promoting the connection between "doing" and "learning". Contrary to traditional views, technoscientific view enforces the view that active manipulation and intervention through experimental activity is an act of constructing our conceptions of what exists in the world and how it does so. To design is not to follow recipes but to act and think creatively (Layton 1993; Mitcham 1994) in order to realize cognitive goals, which can be achieved only through, and merged with,

60 The expert modellers interviewed by the teacher students worked in various fields of science and engineering (including atmospheric science, astrochemistry, bioanalytical chemistry, marine engineering, organometallic chemistry, and materials science). Thus, the study (Tala & Vesterinen 2015) indicates further support for the generalization of the ideas together with the applicability of the method developed in this study, but those results exceed this dissertation.

61 For example, Abd-El-Khalick (1998), Allchin (2011), Clough (2011), Hanuscin et al. (2006), Matthews (1998), Sandoval (2005), Schwartz et al. (2004) and Tala (2013b).

technological devices, experimental machines, measurement instruments, computer soft- and hard-ware. This leaves room for the creativity and also emphasizes the constructive and cognitive aspects of experimentation and modelling. In practice, such a viewpoint encourages, for example, the opening of the black-boxes employed in education; to consider what kind of understanding and assumptions are embodied in the experimental machines and measurement instruments applied in producing and analysing the laboratory phenomena.[62] In such a view, also the “demo effect”, namely the experimental failure in a school lab, is perceived as a rich place to learn both of science and about doing science: In experimental design, failure is understood as a lack of control over nature, and it is always correctable by sharpening both understanding and control over the laboratory phenomena.

Moreover, in the light of reaching material and conceptual control over the phenomena studied, also the typical viewpoint on models and modelling as tools for explaining scientific content has to be extended: If we want school science to reflect useful and fruitful aspects of modelling in physics, we should focus more on new types of creative, generative and simulative modelling building up the connections between and completing the insufficient experimental and theoretical understanding. Instead of trying only to show how models are produced and refined by relying on established theory, we should be able to show how to produce interesting and suggestive new models, and how they can guide the generation of new theoretical insights and guide us in seeking new empirical regularities in phenomena (see Articles II & III). The difficulty of the suggested content of such generative modelling tasks makes implementing these ideas challenging at the lower levels of education. However, some practical solutions of modelling for school science have been conceived in a way highlighting generative features or supporting the development in this direction. Such a model-based generative approach would be quite similar to approaches suggested by Halloun (2007) and Nersessian (1995). Also the practical solution of Crawford & Cullin (2004) fruitfully promotes this objective.

The new views encourage integrative settings. The apparent integration happens between physics or chemistry and technology lessons. Furthermore, the integration of mathematical or IT modelling lessons with modelling in physics could provide a natural place to introduce new perspectives. In those lessons, students may engage more easily in studying the dynamics of models and modelling in the virtual or mathematical world without striving for a direct one-to-one relationship with the physical world, thus enjoying more freedom to explore theoretical ideas. Practising scientists enjoy such freedom, so why not permit the same freedom and

62 Furthermore, the mutual development of conceptual and material control embodied in a simple measurement instrument or experimental setting, such as the mutual development of thermometer or barometer and thermodynamics (e.g., Chang 2004; Middleton 1964), are rich contexts within which to learn from interrupted storylines embedded in hands-on design tasks (Tala 2009b). For example, I included a cut-down example(s) of such a task in school books used in Finnish secondary schools (Tala et al. 2009c). In that attention is paid on the technoscientific design process of the physical quantity, which eventually reveals what science is about. The technoscientific basis of measuring, seems not to be widely discussed in textbooks even in the relatively simple case of thermometer (for a comparative study of how textbooks introduce ‘temperature’ see Radtka 2013)

joy of invention in teaching and schooling? The role of mathematics in physics is then perceived as an essential means to create and develop physical ideas, where mathematical structures themselves can provide new ideas, rather than that of seeing mathematics only as a technical tool for making calculations. Furthermore, emphasizing generative modelling may also encourage the effective and efficient re-organisation and employment of mathematics in physics lessons, that is, not as a rival to empirical activities, but as a natural counterpart to experimentation – as it does in science.

8.3 FURTHER RESEARCH

If the foundation is slanted, the whole building is tilting. For that reason this dissertation study focused on the foundation of education, namely on the analysis of the epistemological basis of physics education and then on the tacit substance of expertise education. The thesis suggests that educational research should carefully consider the views opened by the studies in the philosophy of scientific practises and the special insight opened by the naturalistic approach into the *technoscientific* practises and its practitioners' views. Further studies are needed in developing and testing the above suggested possible practical applications to education at different levels.

Moreover, since there is a lack of understanding about the epistemology and expertise nurtured in contemporary scientific research practices, further field studies could indicate the views of practitioners' employing other methods and working in different fields of science. Such studies can employ the contextualized approach (thereby further developing it) and be developed in close interaction with the education of new scientists or science teachers (sections 8.1 & 8.2). This study is also hoped to encourage more interdisciplinary co-operation in naturalistic studies. The understanding about science developed in deep contextualized discussion between philosophers and practitioners of science are fruitfully facilitated by experts in science education. At best, such an approach opens up new, revolutionary insight on science and its learning and possibilities to every participant (Goldman 1992).

Research groups are kinds of epistemic communities of practice (cf. Lave and Wenger 1991; Wenger 1998) where the ideas and practices are developed in co-operation with others. Here the scientists' shared views were focused as individual apprentices' learning objectives. In further studies, the focus can be moved to the developing understanding and ability of a group, as a shared or interactive cognition. In such processes, understanding and developmental process is shared not only between scientists and engineers but necessarily also embodied in the pieces of experimental and modelling technology developing in the process (see section 4 and Nersessian et al. 2003). These practitioners often have different kinds of epistemic identities. From the viewpoint of productivity and creativity, it would be interesting to study, for example, how knowledge construction together with the connected epistemology and methods develop in different kinds of research groups and in interaction between groups. It would be fruitful to ponder, for example, what the essential features (background defining the epistemic identity, appropriate level of cognitive consensus in a group, compactness of a group, communicative focus, relations between the members) are that constitute of a vital research group. In such research, the benefits of an interdisciplinary approach are evident. In the best case, the projects are shaped by the individual scientists' or group of scientists' interests in development together with the available interdisciplinary resources.

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